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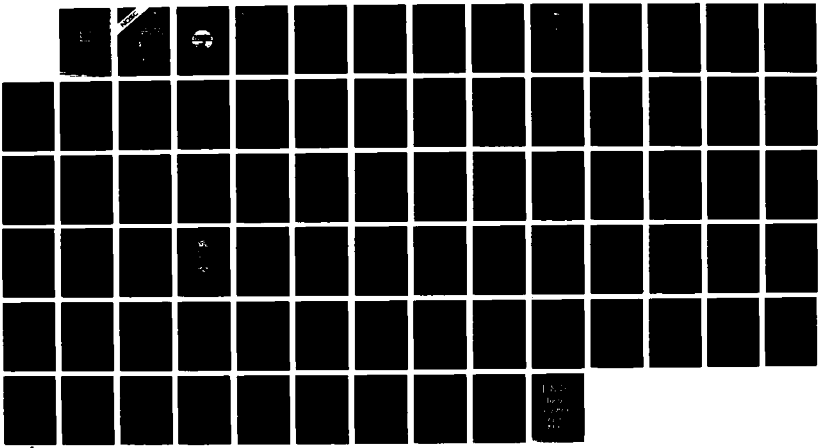

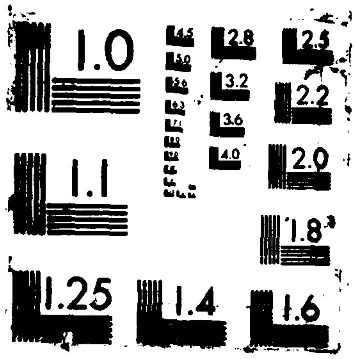
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September 1987

The Design of Impedance-Matching Networks for Broadband Antennas

S. T. Li
D. W. S. Tam

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An interactive BASIC language computer program to aid in the design of a matching network for a broadband antenna is described. Guidelines for the design of a broadband matching network are presented. The Antenna Matching (ANTMAT) program provides a computer-aided design tool for determining network topology and component values of the networks. It improves the speed and accuracy of the broadband matching network design procedures. An optimization algorithm finds the values of the components that minimize the input reflection coefficient. At first, the optimization algorithm with an exponential weighting function is employed for determining a list of network candidates (either a pi network or a T network) from which a network topology is selected. After a topology is specified, the optimization algorithm with other weighting functions is used for finding optimum element values.

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1.0 INTRODUCTION

In a communication system, one of the primary concerns is maximum efficiency in signal transmission and reception. For maximum power transfer there must be an impedance match between the antenna and transmitter (or receiver). A basic problem is to design a coupling network between a given source and a given load so that the transfer of power from the source to the load is maximized over a given frequency band of interest. The device used to perform this impedance matching is called an antenna matching network.

The number of pieces of equipment requiring an antenna connection in some applications may exceed the number of acceptable locations available for antennas. One solution is the use of broadband antennas that have a low VSWR (voltage standing-wave ratio) over the operating band. Broadband antennas are used in conjunction with multicouplers (filters with multiple inputs) to provide a sufficient number of antenna connections.

Ideally a perfect impedance match for maximum power transfer requires 1:1 VSWR at each and every frequency point over the operating frequency band. However, in reality this ideal goal is impossible to achieve for an arbitrary load. When HF antennas are installed on ships, a design goal is that their input impedance be within a specified value of VSWR such as 3:1 VSWR at 50 ohms. When the input VSWR exceeds the specified value of 3:1, the goal is to design an input-impedance-matching network that will bring the VSWR within this limit.

Despite the aid of Smith Charts, the traditional design of an antenna matching network by engineering experience and manual calculation means is an extremely time-consuming task. This report is intended to relieve the engineer of the tedious numerical calculations involved in the network design.

Antenna Matching (ANTMAT), an interactive BASIC language computer program to aid in the design of a matching network for a broadband antenna, has been developed. An optimization algorithm finds the value of the components that minimize the input reflection coefficients. At first, the ANTMAT program uses the optimization algorithm with an exponential weighting function for the determination of a list of network candidates from which a matching network topology is selected. After a topology (either a pi network or a T network)

is specified, the optimization algorithm with other weighting functions finds the values of the components that minimize the input reflection coefficients.

Section 2 presents design guidelines for designing a broadband matching network. In section 3, the optimization algorithm that minimizes the input reflection coefficient is described. Section 4 discusses the menu of various functions which the ANTMAT program performs. A list of hardware and software requirements is also presented. An example is given in section 5 to illustrate the design procedure and the use of the ANTMAT program. The appendix describes mathematically how to produce the Smith Chart.

2.0 BROADBAND MATCHING NETWORK DESIGN GUIDELINES

There exist a number of procedures for designing a broadband matching network (References 1-5). Each broadband antenna has its own inherent impedance characteristics. The degree of success in design is directly related to the experience and ingenuity of the individual matching network designer. Design guidelines for the design of a broadband matching network are given here.

2.1 DEFINITION CIRCLE

Network design decisions are more easily formulated if the broadband antenna impedance data are plotted on a Smith Chart. As an example, consider a typical shipboard broadband antenna operating in the band 2 to 6 MHz. Its antenna impedance values (normalized to 50 + j.0 ohms) for the indicated frequencies in MHz are plotted on the Smith Chart of Figure 2-1.

A design objective circle, also called a definition circle, is shown in Figure 2-1 representing a VSWR of 3:1. This circle is constructed by using 1.0 on the resistance component scale as a center and drawing a circle intersecting 3.0 on the resistance scale. A properly designed matching network will move all of the impedance values within this definition circle.

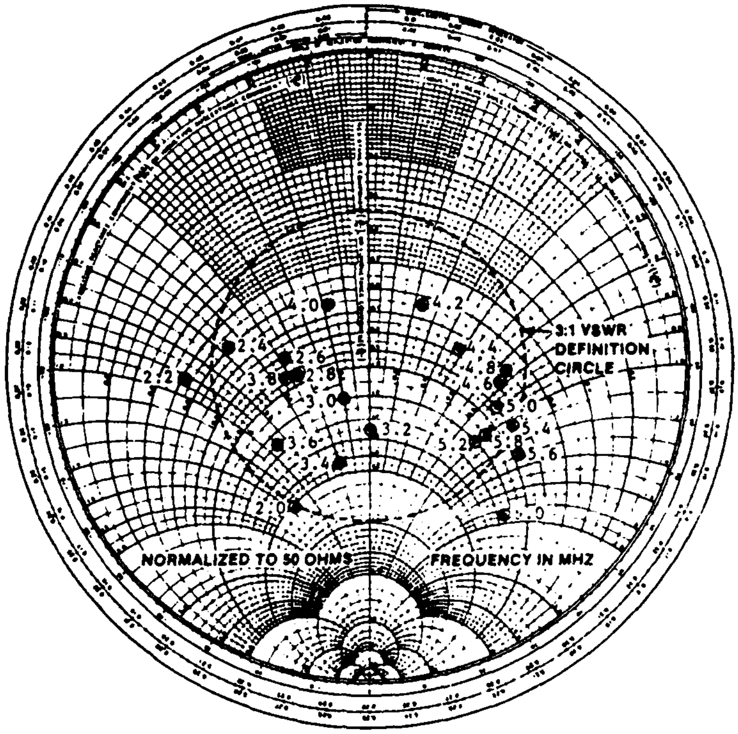


Figure 2-1. Impedance points of a broadband antenna.

2.2 DESIGN GUIDELINES

Number of Components

A component in the broadband matching network is a series or parallel inductor or capacitor. A network should consist of as few components as possible to minimize losses. The fewer the components in a given design, the more efficient will be the resulting network. As an upper limit, very little improvement has been observed with a matching network of more than five components for use with broadband shipboard antennas.

Position of First Component

The first component of the broadband matching network should be incorporated as near as practical to the antenna terminals. An inherent characteristic of any impedance curve, as plotted on the Smith Chart, is that the impedance points "spread out" as the component distance from the antenna terminals increases. Incorporation of matching networks that are far removed from the antenna terminals necessarily reflects reduced matching potential.

The selection of the first component of the matching network is of primary importance. A proper selection provides a better opportunity for achieving the design objective when the remaining components are added.

A Series Component

On a Smith Chart, a series reactance moves impedance values along lines of constant resistance. As depicted in Figure 2-2, a series inductor moves impedance values in a clockwise direction and a series capacitor moves the impedance values in a counterclockwise direction on the Smith Chart. Also, a series inductor moves the higher frequency values farther along the constant-resistance lines than the lower frequency values. In contrast, a series capacitor moves the lower frequency values farther than the higher frequency values.

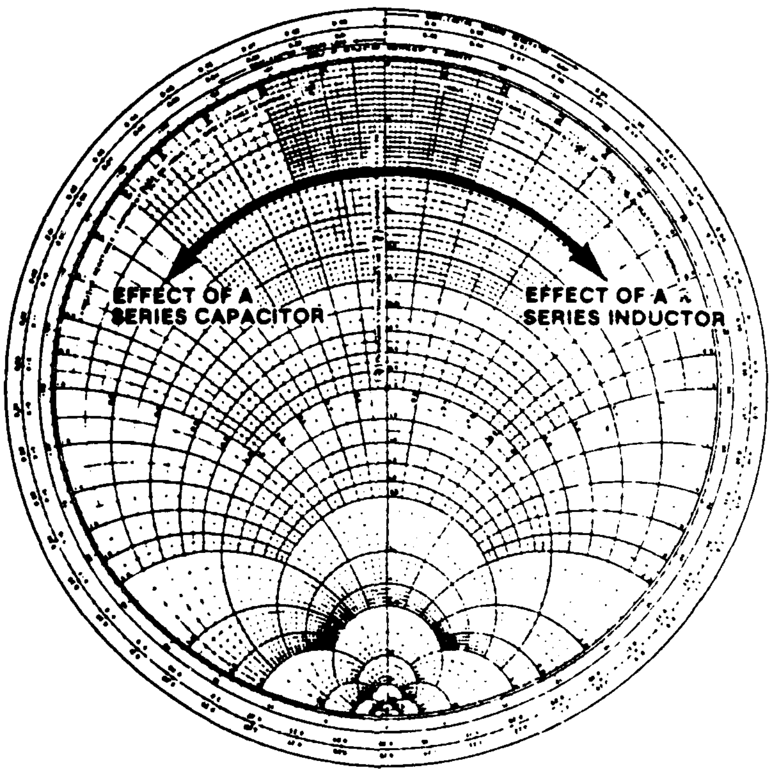


Figure 2-2. The effect of a series inductor/capacitor for matching-network calculation.

A Parallel Component

A shunt reactance moves admittance values (inverse impedance values) along lines of constant conductance. In practice, the constant-conductance lines can be visualized by overlaying a reversed transparent Smith Chart on top of another Smith Chart so that zero impedance on one chart is over infinite impedance on the other. As depicted in the "reversed" Smith Chart in Figure 2-3, a parallel inductor moves admittance values in the counter-clockwise direction on the "reversed" Smith Chart. A parallel capacitor moves admittance values in the opposite direction. Also, a parallel inductor moves the lower frequency values farther along the constant-conductance lines than the higher frequency values, and a parallel capacitor moves the higher frequency values farther than the lower frequency values.

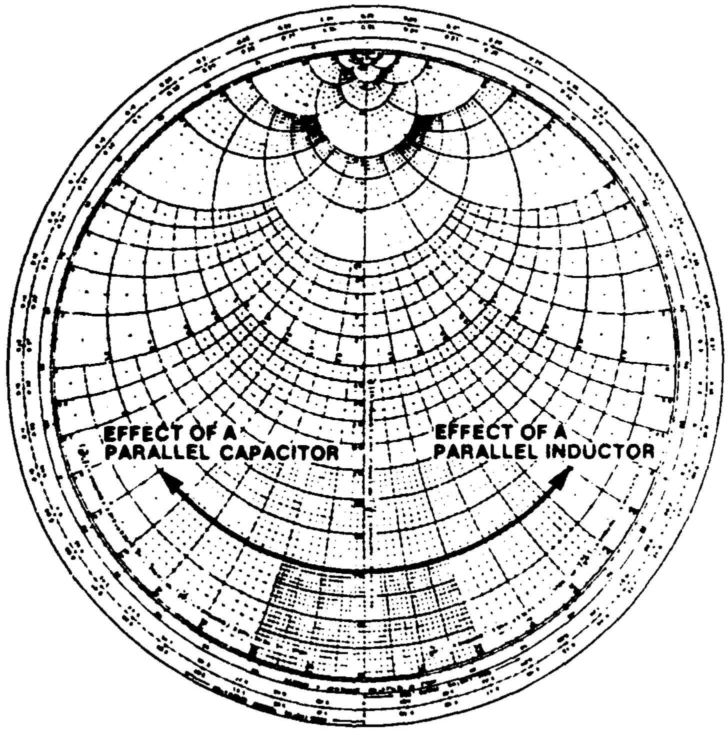


Figure 2-3. The effect of a parallel inductor/ capacitor for matching-network calculation.

Selection of Series or Parallel Component

The selection of a series or parallel component can be facilitated by Figure 2-4. A definition circle (a design objective circle) is shown representing a design objective of 3:1 VSWR. Circle A is constructed tangent to the definition circle at the maximum R value and passes through the point

of infinity. Circle B is constructed tangent to the definition circle at the minimum R value and also passes through the point of infinity. The area enclosed by circle B, but outside of circle A and the definition circle, is shaded. As a general guideline, if an impedance point falls within this shaded area, this point can be moved toward the definition circle using series elements. Impedance points outside the shaded area can be moved toward the definition circle by using parallel elements.

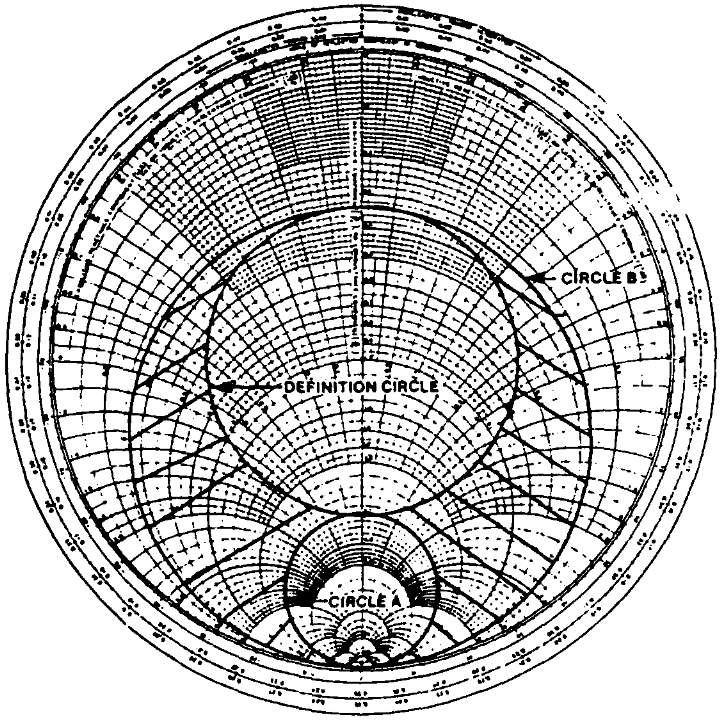


Figure 2-4. Smith Chart showing definition circle and boundaries of using series component.

Practical Range of Component Values

In general, for the HF frequency band (2-30 MHz), inductors should be in the range of 0.25 μH to 12 μH. Capacitors usually should be in range of 50 pF to 2500 pF. Initial component values, as well as the final design component values, should remain within these practical ranges. The establishment of practical ranges is based on physical size considerations.

3.0 AN OPTIMIZATION ALGORITHM FOR DESIGNING A BROADBAND MATCHING NETWORK

3.1 THE MINIMIZATION OF VSWR

The objective of designing a broadband matching network is to minimize VSWR over the operating frequency band. VSWR is defined as:

$$\mathrm{VSWR} = \frac{1 + |\Gamma|}{1 - |\Gamma|} \tag{3-1}$$

where Γ is the voltage reflection coefficient.

Figure 3-1 shows an antenna with matching network.

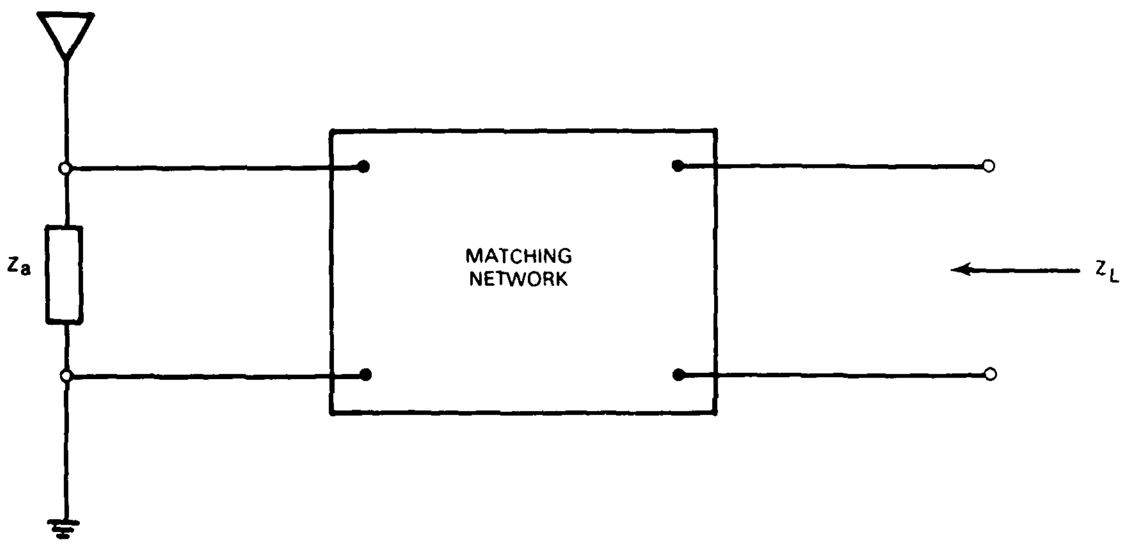


Figure 3-1. Antenna with matching network.

Z_a is the antenna impedance. Z_L is the impedance at the matching-network terminal. Z_o is the characteristic impedance, which is 50 ohms for the Navy shipboard application. The voltage reflection coefficient can be expressed as:

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} \tag{3-2}$$

Consider a frequency band consisting of N frequencies, f_i, i = 1, 2, ..., N. The impedance at the matching-network terminal at each frequency f_i is Z_{L_i}. The reflection coefficient at each frequency is then:

$$\Gamma_i = \frac{Z_{L_i} - 50}{Z_{L_i} + 50} \quad \text{where } i = 1, 2, 3, \ldots, N \tag{3-3}$$

A minimum VSWR in the specified frequency range can be obtained by minimizing:

$$f(p_1,p_2,p_3) = \sum_{i=1}^{N} |\Gamma_i|^2, \tag{3-4}$$

where p_1, p_2, and p_3 are component values of a desired matching network which consists of three branches.

The desired matching network is a lossless two-port network, which can be realized as either a pi network or a T network as shown in Figures 3-2 and 3-3, respectively. The pi (or T) network has three branches. There are six possible types of elements (L, C, L-C parallel, L-C series, short-series, and open-parallel) for each branch of the pi (or T) network, except as limited by the following rules:

1. L-C parallel should not be used for a series branch.
2. L-C series should not be used for a parallel branch.
3. Short-series should not be used for a parallel branch.
4. Open-parallel should not be used for a series branch.

Figure 3-4 shows the six possible types of elements. Each type of element may have two components, one component, or zero components. For examples, an L-C parallel element consists of two components, but a short-series element has no circuit component.

Since $f(p_1, p_2, p_3)$ is a continuous and differentiable function, it can be minimized by any method of optimization. The method of Steepest Descent (Reference 6) is used here. The algorithm of Steepest Descent is summarized as follows:

Step 1 Section an initial set of values for p_i. This corresponds to a point $\bar{p}_o$ in the three-dimensional space p_i, i = 1, 2, 3, where $\bar{p}_o = (p_1^o, p_2^o, p_3^o)$.

Step 2 Calculate $\nabla f(\bar{p}^s)$, the gradient of the function f at the s^{th} point, $\bar{p}^s$, where s denotes the s^{th} iteration, s = 0, 1, 2, ...

Step 3 Choose a value of t that minimizes $f[(\bar{p}^s - t \cdot \nabla f(\bar{p}^s))]$, where t is called the step size.

Step 4 Calculate the next point $\bar{p}^{s+1}$ as $\bar{p}^{s+1} = \bar{p}^s - t \cdot \nabla f(\bar{p}^s)$, that is

$$p_1^{s+1} = p_1^s - t \cdot \left.\frac{\partial f}{\partial p_1}\right|_{p_1^s, p_2^s, p_3^s},$$

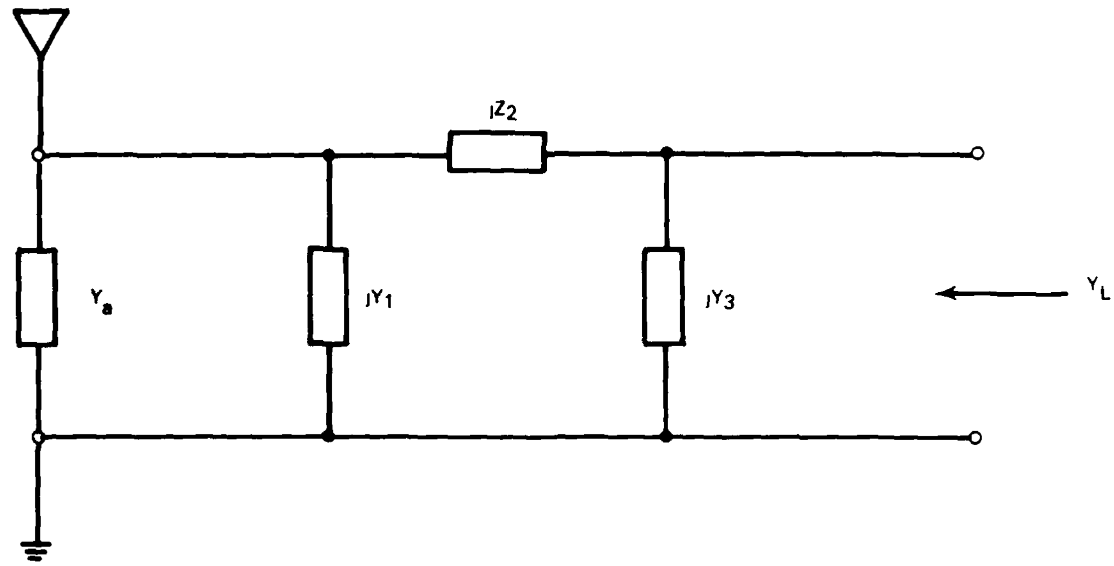


Figure 3-2. Antenna with π matching network.

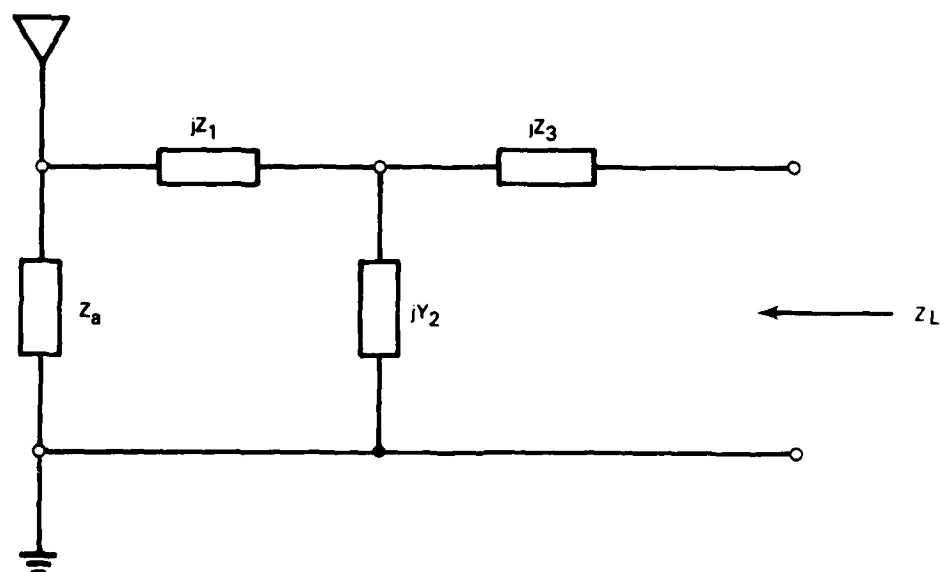


Figure 3-3. Antenna with T matching network.

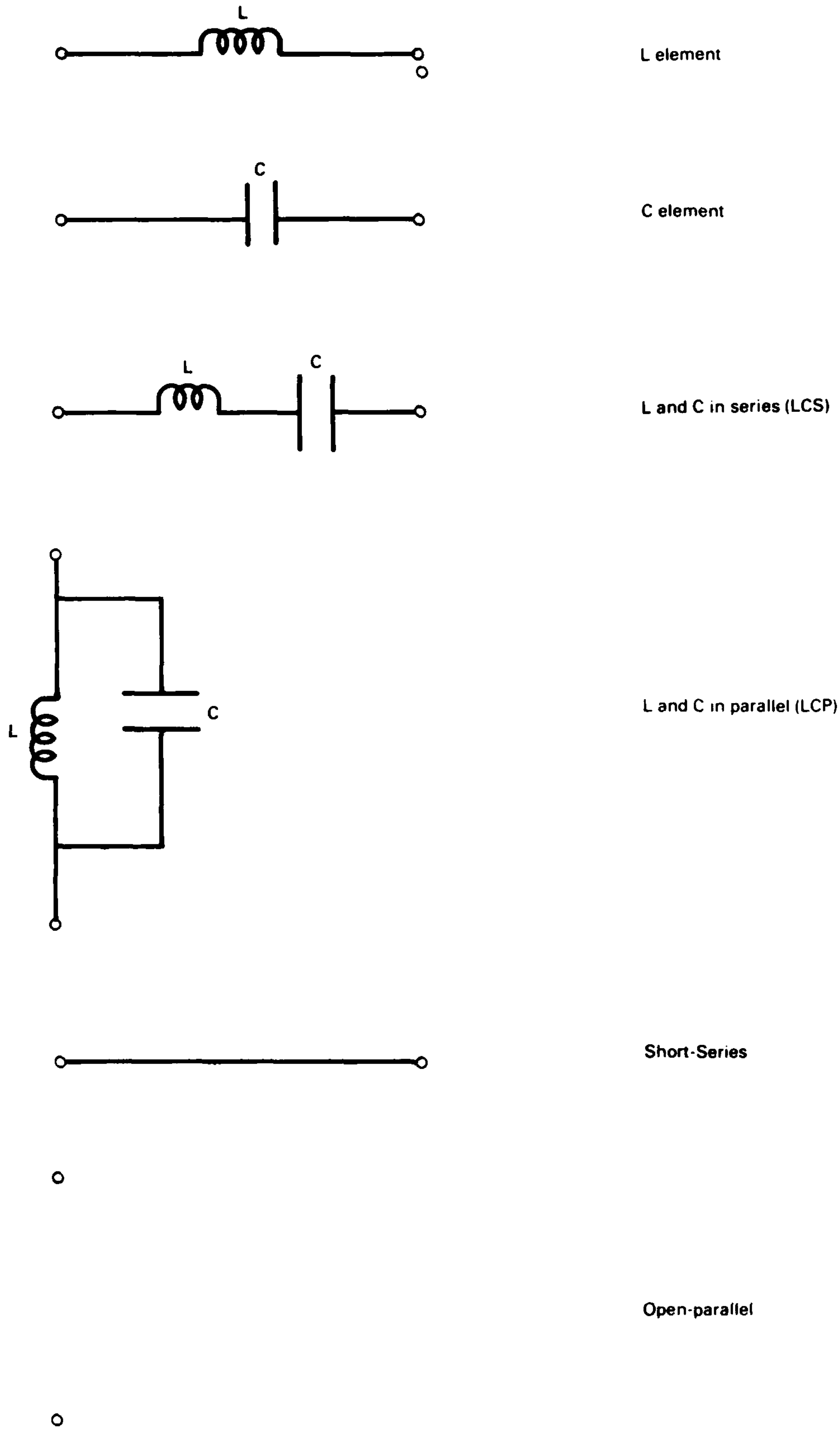


Figure 3-4. Six possible types of elements in a branch.

$$p_2^{s+1} = p_2^s - t \cdot \left.\frac{\partial f}{\partial p_2}\right|_{p_1^s, p_2^s, p_3^s} ,$$

$$p_3^{s+1} = p_3^s - t \cdot \left.\frac{\partial f}{\partial p_3}\right|_{p_1^s, p_2^s, p_3^s} .$$

Step 5 Terminate the calculation if $f(\overline{p}^s) - f(\overline{p}^{s+1}) \leq \epsilon$, where ϵ is a preassigned tolerance. If $f(\overline{p}^s) - f(\overline{p}^{s+1}) > \epsilon$, return to Step 2 and continue the iteration until the criteria are met. For the purpose of our calculations, ϵ was chosen to be 10^{-6}, and the number of iterations was chosen to be between 30 and 60 iterations for the determination of network candidates and between 100 and 200 iterations for the optimization of the selected network.

There are two possible network topologies: a pi or a T network. The necessary equations for each of the topologies will be derived. The derivations are obtained from Reference 7.

3.2 PI NETWORK TOPOLOGY

Consider a pi matching network consisting of three branches. As shown in Figure 3-2, jY_1 designates the admittance of the first branch, jZ_2 the impedance of the second branch, and jY_3 the admittance of the third branch. Y_L is the admittance at the terminals of the matching network when connected to the antenna. For the i^{th} impedance/frequency pair of values, the reflection coefficient can be written as:

$$\Gamma_i = \frac{1 - 50Y_{L_i}}{1 + 50Y_{L_i}} , \tag{3-5}$$

where

$$Y_{L_i} = \frac{1}{\dfrac{1}{Y_{a_i} + jY_{1_i}} + jZ_{2_i}} + jY_{3_i}$$

$$= \frac{Y_{a_i}\left(1 - Y_{3_i}Z_{2_i}\right) + j\left(Y_{1_i} + Y_{3_i} - Y_{1_i}Z_{2_i}Y_{3_i}\right)}{\left(1 - Z_{2_i}Y_{1_i}\right) + jZ_{2_i}Y_{a_i}} . \tag{3-6}$$

One can then calculate $f = \sum_{i=1}^{N} |\Gamma_i|^2$ with

$$\Gamma_i = \frac{\left(1-Y_{1_i}Z_{2_i}\right) + jY_{a_i}Z_{2_i} - 50\left[Y_{a_i}\left(1-Z_{2_i}Y_{3_i}\right) + j\left(Y_{1_i} + Y_{3_i} - Y_{1_i}Z_{2_i}Y_{3_i}\right)\right]}{\left(1-Y_{1_i}Z_{2_i}\right) + jY_{a_i}Z_{2_i} + 50\left[Y_{a_i}\left(1-Z_{2_i}Y_{3_i}\right) + j\left(Y_{1_i} + Y_{3_i} - Y_{1_i}Z_{2_i}Y_{3_i}\right)\right]}$$

$$= \frac{\left(\frac{1}{Y_{1_i}Z_{2_i}} - 1\right) + j\frac{Y_{a_i}}{Y_{1_i}} - 50\left[Y_{a_i}\left(\frac{1}{Y_{1_i}Z_{2_i}} - \frac{Y_{3_i}}{Y_{1_i}}\right) + j\left(\frac{1}{Z_{2_i}} + \frac{Y_{3_i}}{Y_{1_i}Z_{2_i}} - Y_{3_i}\right)\right]}{\left(\frac{1}{Y_{1_i}Z_{2_i}} - 1\right) + j\frac{Y_{a_i}}{Y_{1_i}} + 50\left[Y_{a_i}\left(\frac{1}{Y_{1_i}Z_{2_i}} - \frac{Y_{3_i}}{Y_{1_i}}\right) + j\left(\frac{1}{Z_{2_i}} + \frac{Y_{3_i}}{Y_{1_i}Z_{2_i}} - Y_{3_i}\right)\right]} \qquad (3\text{-}7)$$

Let $G_1 = Y_{3_i}$, $G_2 = 1/Z_{2_i}$, $G_3 = 1/Y_{1_i}$.

One can write

$$\Gamma_i = \frac{\left(G_2G_3 - 1\right) + j\,Y_{a_i}G - 50\left[Y_{a_i}\left(G_2G_3 - G_1G_3\right) + j\left(G_1G_2G_3 - G_1 + G_2\right)\right]}{\left(G_2G_3 - 1\right) + j\,Y_{a_i}G + 50\left[Y_{a_i}\left(G_2G_3 - G_1G_3\right) + j\left(G_1G_2G_3 - G_1 + G_2\right)\right]} \qquad (3\text{-}8)$$

Let

$$Y_3 = Y_3^o - ts_3^o,$$

$$Z_2 = Z_2^o - ts_2^o,$$

$$\frac{1}{Z_2} = \frac{1}{Z_2^o}\left(1 - t \cdot \frac{s_2^o}{Z_2^o}\right)^{-1} = \frac{1}{Z_2^o} + t \cdot \frac{s_2^o}{(Z_2^o)^2} + \ldots . \qquad (3\text{-}9)$$

$$Y_1 = Y_1^o - ts_1^o,$$

$$\frac{1}{Y_1} = \frac{1}{Y_1^o}\left(1 - t \cdot \frac{s_2^o}{Y_1^o}\right)^{-1} = \frac{1}{Y_1^o} + t \cdot \frac{s_1^o}{(Y_1^o)^2} + \ldots ,$$

where "o" denotes the values obtained from previous iteration. s_1^o, s_2^o, and s_3^o are defined as

$$s_1^o = K_1 \cdot \left.\frac{\partial f}{\partial p_1}\right|_{p_1^o,p_2^o,p_3^o},$$

where

$$K_1 = \begin{cases} \dfrac{-1}{\omega_i (L_1^o)^2} & , \text{ if } p_1 = L_1 \\ \omega_i & , \text{ if } p_1 = C_1 \\ \dfrac{-1}{\omega_i (L_1^o)^2} + \omega_i & , \text{ if } p_1 \text{ is } L_1 - C_1 \text{ parallel} \\ 0 & , \text{ if } p_1 \text{ is open-parallel} \end{cases} \tag{3-10}$$

$$s_2^o = K_2 \cdot \left. \frac{\partial f}{\partial p_2} \right|_{p_1^o, p_2^o, p_3^o},$$

where

$$K_2 = \begin{cases} \omega_i & , \text{ if } p_2 = L_2 \\ \dfrac{-1}{\omega_i (C_2^o)^2} & , \text{ if } p_2 = C_2 \\ \dfrac{-1}{\omega_i (C_2^o)^2} + \omega_i & , \text{ if } p_2 \text{ is } L_2 - C_2 \text{ series} \\ 0 & , \text{ if } p_2 \text{ is short-series} \end{cases} \tag{3-11}$$

$$s_3^o = K_3 \cdot \left. \frac{\partial f}{\partial p_3} \right|_{p_1^o, p_2^o, p_3^o},$$

where

$$K_1 = \begin{cases} \dfrac{-1}{\omega_i (L_3^o)^2} & , \text{ if } p_3 = L_3 \\ \omega_i & , \text{ if } p_3 = C_3 \\ \dfrac{-1}{\omega_i (L_3^o)^2} + \omega_i & , \text{ if } p_3 \text{ is } L_3 - C_3 \text{ parallel} \\ 0 & , \text{ if } p_3 \text{ is open-parallel} \end{cases} \tag{3-12}$$

one obtains

$$\begin{aligned} G_1 &= G_1^o - th_1^o \\ G_2 &= G_2^o - th_2^o \\ G_3 &= G_3^o - th_3^o , \end{aligned} \tag{3-13}$$

where

$$h_1^o = s_3^o \,,$$

$$h_2^o = -\frac{s_2^o}{(Z_2^o)^2} \tag{3-14}$$

$$h_3^o = -\frac{s_1^o}{(Y_1^o)^2} \,.$$

Substituting Equation (3-14) into (3-8), one can get

$$\Gamma_i = \frac{A_1 + B_1 t + C_1 t^2 + j50 h_1 h_2 h_3 t^3}{D_1 + E_1 t + F_1 t^2 - j50 h_1 h_2 h_3 t^3} \,. \tag{3-15}$$

Since t is very small, the term $50h_1h_2h_3t^3$ can be neglected. Γ_i can be reduced to a ratio of two quadrates as

$$\Gamma_i = \frac{A_1 + B_1 t + C_1 t^2}{D_1 + E_1 t + F_1 t^2} \,, \tag{3-16}$$

where

$$A_1 = (G_2G_3 - 1) + jY_{a_i}G_3 - 50\left[Y_{a_i}(G_2G_3 - G_1G_3) + j(G_1G_2G_3 - G_1 + G_2)\right]$$

or

$$A_1 = P_2 - P_1 \,,$$

letting $P_2 = (G_2G_3 - 1) + jY_{a_i}G_3$

$$P_1 = 50\left[Y_{a_i}(G_2G_3 - G_1G_3) + j(G_1G_2G_3 - G_1 + G_2)\right]$$

$$D_1 = P_2 + P_1$$

$$B_1 = -(G_2h_3+G_3h_2) + jY_{a_i}h_3 - 50\Big[Y_{a_i}(G_1h_3+G_3h_1-G_2h_3-G_3h_2)$$
$$+ j(h_1-h_2-G_1G_2h_3-G_2G_3h_1-G_1G_3h_2)\Big]$$

or

$$B_1 = Q_2 - Q_1 \,,$$

while letting

$$Q_2 = -(G_2h_3 + G_3h_2) - jY_{a_i}h_3$$

and

$$Q_1 = 50Y_{a_i}\left[(G_1h_3+G_3h_1-G_2h_3-G_2h_3-G_3h_2) + j(h_1-h_2-G_1G_2h_3-G_2G_3h_1-G_1G_3h_2)\right]$$

$$E_1 = Q_2 + Q_1$$

$$C_1 = h_2h_3 - 50Y_{a_i}\left[(h_2h_3-h_1h\ ) + j(h_1h_2G_3+h_1h_3G_2+h_2h_3G_1)\right]$$

$$C_1 = R_2 - R_1$$

while letting

$$R_2 = h_2h_3$$

and

$$R_1 = 50Y_{a_i}\left[(h_2h_3-h_1h_2) + j(h_1h_2G_3+h_1h_3G_2+h_2h_3G_1)\right]$$

$$F_1 = R_2 + R_1 \ .$$

Equation (15) can be approximated, assuming t small, as

$$\Gamma_1 = \frac{A_1}{D_1} + t \cdot \left(\frac{B_1D_1 - A_1E_1}{D_1^2}\right) + t^2 \cdot \left[\frac{C_1\cdot D_1^2 - (A_1\cdot D_1\cdot F_1 + B_1\cdot D_1\cdot E_1) + A_1\cdot E_1^2}{D_1^3}\right]$$

or

$$\Gamma_i = a_i + b_it + c_it^2 \ , \qquad (3\text{-}17)$$

where

$$a_i = \frac{A_1}{D_1}$$

$$b_i = \frac{B_1}{D_1} - \frac{A_1E_1}{D_1^2}$$

and

$$c_i = \frac{C_1}{D_1} - \frac{A_1F_1 + B_1E_1}{D_1^2} + \frac{A_1E_1^2}{D_1^3} \ .$$

Since $|\Gamma_i|^2 = \Gamma_i\Gamma_i^* = (a_i + b_i t + c_i t^2)(a_i^* + b_i^* t + c_i^* t^2)$, one can then write

$$f = \sum_{i=1}^{N} |\Gamma_i| R^2 = A' + B't + C't^2 , \tag{3-18}$$

where

$$A' = \mathrm{Re} \sum_{i=1}^{N} a_i a_i^* ,$$

$$B' = \mathrm{Re} \sum_{i=1}^{N} (a_i^* b_i + a_i b_i^*) ,$$

$$C' = \mathrm{Re} \sum_{i=1}^{N} (b_i b_i^* + a_i c_i^* + a_i^* c_i) .$$

Note that A', B' and C' are all real numbers.

To obtain the minimum of $\sum_{i=1}^{N} |\Gamma_i|^2$, one must have

$$2C't + B' = 0.$$

Therefore, the step size t can be calculated as

$$t = -\frac{B'}{2C'} . \tag{3-19}$$

After the step size t is obtained, the desired component values can be calculated from the last iteration as described in Step 4 of the algorithm discussed in section 3.1.

3.3 T NETWORK TOPOLOGY

For a T-type network as shown in Figure 3-3, where jZ_1 and jZ_3 designate impedances and jY_2 denotes admittance, one can calculate the load impedance at the terminals of the matching network as

$$Z_L = \frac{1}{\dfrac{1}{z_a + jZ_1} + jY_2} + jZ_3 \tag{3-20}$$

or

$$= \frac{Z_{a_i}\left(1-Y_{2_i}Z_{3_i}\right) + j\left(Z_{1_i}+Z_{3_i}-Z_{1_i}Y_{2_i}Z_{3_i}\right) - 50\left(1-Z_{1_i}Y_{2_i}+jY_{2_i}Z_{a_i}\right)}{Z_{a_i}\left(1-Y_{2_i}Z_{3_i}\right) + j\left(Z_{1_i}+Z_{3_i}-Z_{1_i}Y_{2_i}Z_{3_i}\right) + 50\left(1-Z_{1_i}Y_{2_i}+jY_{2_i}Z_{a_i}\right)} , \quad (3\text{-}21)$$

and thus $f = \sum_{i=1}^{N} |\Gamma_i|^2$ can be obtained.

Similarly, it can be shown that

$$Z_{1_i} = Z^o_{1_i} - t \cdot s^o_1 ,$$

$$Y_{2_i} = Y^o_{2_i} - t \cdot s^o_2 , \quad (3\text{-}22)$$

$$Z_{3_i} = Z^o_{3_i} - t \cdot s^o_2 ,$$

where

$$s^o_1 = K_1 \cdot \frac{\partial f}{\partial p_1}\bigg|_{p^o_1, p^o_2, p^o_3},$$

$$K_1 = \begin{cases} \omega_i & , \text{ if } p_1 = L_1 \\ \dfrac{-1}{\omega_i (C^o_1)^2} & , \text{ if } p_1 = C_1 \\ \dfrac{-1}{\omega_i (C^o_1)^2} + \omega_i & , \text{ if } p_1 \text{ is } L_1 - C_1 \text{ series} \\ 0 & , \text{ if } p_1 \text{ is short-series} \end{cases} \quad (3\text{-}23)$$

$$s^o_2 = K_2 \cdot \frac{\partial f}{\partial p_2}\bigg|_{p^o_1, p^o_2, p^o_3},$$

$$K_2 = \begin{cases} \dfrac{-1}{\omega_i (L^o_2)^2} & , \text{ if } p_2 = L_2 \\ \omega_i & , \text{ if } p_2 = C_2 \\ \dfrac{-1}{\omega_i (L^o_2)^2} + \omega_i & , \text{ if } p_2 \text{ is } L_2 - C_2 \text{ parallel} \\ 0 & , \text{ if } p_2 \text{ is open-parallel} \end{cases} \quad (3\text{-}24)$$

$$s_3^o = K_3 \cdot \left.\frac{\partial f}{\partial p_3}\right|_{p_1^o, p_2^o, p_3^o},$$

$$K_1 = \begin{cases} \omega_i & , \quad \text{if } p_3 = L_3 \\ \dfrac{-1}{\omega_i (C_3^o)^2} & , \quad \text{if } p_3 = C_3 \\ \dfrac{-1}{\omega_i (C_3^o)^2} + \omega_i & , \quad \text{if } p_3 \text{ is } L_3 - C_3 \text{ series} \\ 0 & , \quad \text{if } p_3 \text{ is short-series} \end{cases} \tag{3-25}$$

Substituting Equation (22) into Equation (21), and since

$$Z_{1_i} Y_{2_i} = Z_{1_i}^o Y_{2_i}^o - t\left[s_1^o Y_{2_i}^o + s_2^o Z_{1_i}^o\right] + t^2 s_i^o s_2^o ,$$

$$Y_{2_i} Z_{3_i} = Y_{2_i}^o Z_{3_i}^o - t\left[s_2^o Z_{3_i}^o + s_3^o Y_{2_i}^o\right] + t^2 s_2^o s_3^o ,$$

$$Z_{1_i} Y_{2_i} Z_{3_i} = Z_{1_i}^o Y_{2_i}^o Z_{3_i}^o - t\left[s_1^o Y_{2_i}^o Z_{3_i}^o + s_2^o Z_{1_i}^o Z_{3_i}^o + s_3^o Z_{1_i}^o Y_{3_i}^o\right]$$

$$+ t^2\left[s_1^o s_2^o Z_{3_i}^o + s_2^o s_3^o Z_{1_i}^o + s_1^o s_3^o Y_{2_i}^o\right] ,$$

one can write

$$\Gamma_i = \frac{A_1 + B_1 t + C_1 t^2}{D_1 + E_1 t + F_1 t^2} , \tag{3-26}$$

where

$$A_1 = Z_{a_i}\left(1 - Y_{2_i}^o Z_{3_i}^o\right) + j\left(Z_{1_i}^o + Z_{3_i}^o - Z_{1_i}^o Y_{2_i}^o Z_{3_i}^o\right) - 50\left(1 - Z_{1_i}^o Y_{2_i}^o + j Y_{2_i}^o Z_a\right)$$

or

$$A_1 = P_2 - P_1 ,$$

while letting

$$P_1 = Z_{a_i}\left(1 - Y^o_{2_i} Z^o_{3_i}\right) + j\left(Z^o_{1_i} + Z^o_{3_i} - Z^o_{1_i} Y^o_{2_i} Z^o_{3_i}\right) ,$$

$$P_1 = 50\left(1 - Z^o_{1_i} Y^o_{2_i}\right) + jY^o_{2_i} Z_{a_i} ,$$

$$D_1 = P_1 + P_2 .$$

$$B_1 = \left[Z_{a_i}\left(s^o_2 Z^o_{3_i} + s^o_3 Y^o_{2_i}\right) + j\left(s^o_1 Y^o_{2_i} Z^o_{3_i} + s^o_2 Z^o_{1_i} Z^o_{3_i} + s^o_3 Z^o_{1_i} Y_{2_i} - s^o_1 - s^o_3\right)\right]$$

$$-50\left(s^o_1 Y^o_{2_i} + s^o_2 Z^o_{1_i} - js^o_2 Z_{a_i}\right)$$

or

$$B_1 = Q_2 + Q_1 ,$$

while letting

$$Q_2 = Z_{a_i}\left(s^o_2 Z^o_{3_i} + s^o_3 Y^o_{2_i}\right) + j\left(s^o_1 Y^o_{2_i} Z^o_{3_i} + s^o_2 Z^o_{1_i} Z^o_{3_i} + s^o_3 Z^o_{1_i} Y^o_{2_i} - s^o_1 - s^o_3\right) ,$$

$$Q_1 = 50\left(s^o_1 Y^o_{2_i} + s^o_2 Z^o_{1_i} - js^o_2 Z_{a_i}\right) ,$$

$$E_1 = Q_1 + Q_2 .$$

$$C_1 = -s^o_2 s^o_3 Z^o_{a_i} - j\left(s^o_1 s^o_2 Z^o_{3_i} + s^o_2 s^o_3 Z^o_{1_i} + s^o_1 s^o_3 Y^o_{2_i}\right) + 50 s^o_1 s^o_2$$

or

$$C_1 = R_2 - R_1 ,$$

while letting

$$R_2 = s^o_2 s^o_3 Z^o_{a_i} - j\left(s^o_1 s^o_2 Z^o_{3_i} + s^o_2 s^o_3 Z^o_{1_i} + s^o_1 s^o_3 Y^o_{2_i}\right) ,$$

$$R_1 = -50\, s^o_1 s^o_2 ,$$

$$F_1 = R_1 + R_2 .$$

Equation (26) can be approximated for t small as

$$\Gamma_i = \frac{A_1}{D_1} + t\left(\frac{B_1}{D_1} - \frac{A_1 \cdot E_1}{D_1^2}\right) + t^2\left(\frac{C_1}{D_1} - \frac{A_1F_1 + B_1E_1}{D_1^2} + \frac{A_1 \cdot E_1{}^2}{D_1^3}\right) + \ldots .$$

or

$$\Gamma_i = a_i + b_it + c_it^2 , \tag{3-27}$$

where

$$a_i = \frac{A_1}{D_1}$$

$$b_i = \frac{B_1}{D_1} - \frac{A_1E_1}{D_1^2}$$

$$c_i = \frac{C_1}{D_1} - \frac{A_1F_1 + B_1E_1}{D_1^2} + \frac{A_1E_1^2}{D_1^3}$$

$$\sum_{i=1}^{N} |\Gamma_i|^2 \simeq \sum_{i=1}^{N} \left(a_i + b_it + c_it^2\right)\left(a_i^* + b_i^*t + c_i^*t^2\right)$$

$$\simeq \sum_{i=1}^{N} a_ia_i^* + t \cdot \sum_{i=1}^{N} \left(a_i^*b_i + a_ib_i^*\right) + t^2 \sum_{i=1}^{N} \left(b_ib_i^* + a_ic_i^* + a_i^*c_i\right)$$

or

$$\sum_{i=1}^{N} |\Gamma_i|^2 \simeq A' + B't + C't^2 ,$$

where

$$A' = \mathrm{Re}\left(\sum_{i=1}^{N} a_ia_i^*\right)$$

$$B' = \mathrm{Re}\left(\sum_{i=1}^{N} \left(a_i^*b_i + a_ib_i^*\right)\right)$$

$$C' = \mathrm{Re}\left(\sum_{i=1}^{N} \left(b_ib_i^* + a_ic_i^* + a_i^*c_i\right)\right) .$$

Note that A', B' and C' are all real numbers.

To obtain the minimum of $\sum_{i=1}^{N} |\Gamma_i|^2$ one must have

$$2C't + B' = 0 \ .$$

Therefore, the step size t can be calculated as

$$t = -\frac{B'}{2C'} \ . \tag{3-28}$$

After the step size t is obtained, the desired component values can be calculated from the last iteration as described in Step 4 of the algorithm discussed in section 3.1.

3.4 WEIGHTED OPTIMIZATION FUNCTION

As an alternative, $\sum_{i=1}^{N} |\Gamma_i|^2$ can be replaced by a weighted optimization function, which is

$$f = \sum_{i=1}^{N} W_i |\Gamma_i|^2 \ , \tag{3-29}$$

where W_i is a weighting factor that can either be chosen by the user or calculated by the program. The use of weights allows the user to put more emphasis in the matching over certain portions of the frequency range. The weights can be chosen by the user or calculated by the program. There are four options available to the user for selecting weights:

1. Exponential weighting function.
2. Around-the-average weighting function.
3. User input weights on selected frequencies.
4. Weight is 1 on all frequency points.

In the first option, the weighting factor is assumed to be in proportion to some exponent of the VSWR. The values of the exponent must be greater than one which may be specified by the user. If the user does not specify an exponent value, an exponent of 1.02 is used in the program. The larger the exponent is, the more weight is put on the impedance point which has a high VSWR. It will pull this impedance point into the definition circle on the Smith Chart quickly. However, it may push another impedance point which has a low VSWR outside the definition circle. The weighting factor is calculated by the following expression:

$$W_i = \begin{cases} 1 & \text{, if } VSWR_i \le v \\ (VSWR_i)^e & \text{, if } VSWR_i > v \end{cases} \tag{3-30}$$

where W_i = new weighting factor

$VSWR_i$ = current VSWR value

v = 1.0, if user does not input any value

e = 1.02, if user does not input any value

The exponential weighting function option with an exponent of 1.02 is used in the determination of network topology procedure.

The second option is intended to bring each VSWR to a narrow region around its average value. This option is used when the average VSWR value is less than the required VSWR value (say 3:1). A weighting factor is assigned to each frequency point when its VSWR is greater than the average VSWR value in accordance with the following calculations:

$$W_i = \begin{cases} LI \cdot \text{Maximum}(W_c, W_{old}) & \text{, if } VSWR_i > AVSWR \\ W_{old} & \text{, if } VSWR_i \le AVSWR \end{cases}, \tag{3-31}$$

where

W_i = new weighting factor

W_c = CONST $\cdot$ ($VSWR_i$ - AVSWR) + 1

CONST = First multiplier for average weighting

= 2, if user does not input any value

$VSWR_i$ = Current VSWR value

AVSWR = Average VSWR value

W_{old} = Current weighting factor

LI = Second multiplier for average weighting

= 1, if user does not input any value. However, if W_{old} = 1, then LI must be 1.

$$\text{Maximum}(W_c, W_{old}) = \begin{cases} W_c, & \text{if } W_c > W_{old} \\ W_{old}, & \text{if } W_c \le W_{old} \end{cases}$$

The third option gives user a chance to change weighting factor at any selected frequency. This option allows the user to put more emphasis in certain selected frequencies according to the user's engineering judgment.

The last option sets the weighting factor to 1 on all frequency points.

4.0 AN ANTENNA MATCHING PROGRAM

4.1 OVERVIEW OF THE ANTMAT PROGRAM

The ANTMAT program is based on the optimization algorithm described in section 3 to aid in design of a matching network for a broadband antenna. It is written by using Microsoft's BASIC language. The ANTMAT is a function-driven program. That is, the user is given a menu of the various functions that the program can perform. From this menu, the user selects the function or sequencing of functions that allows him to carry out the desired operation. The menu of the various functions are:

1. Read antenna impedance file.
2. Determine network candidates.
3. Optimize selected network.
4. Adjust component value manually.
5. List network candidates.
6. Digitize impedance plot from tablet.
7. Exit.

Because it is of a function-oriented nature, ANTMAT is driven by a main routine (called "menu driver") that waits for a command entered via the function key, processes this command, returns to the menu driver, and continues in this manner until the exit function is chosen. The structure of the ANTMAT program is shown in figure 4-1. Each function of operations will be discussed in the following sections. Usually, the user selects a sequence of operations for designing an antenna matching network. An example of these operations is shown in Figure 4-2. However, the user is free to select other sequences of operations.

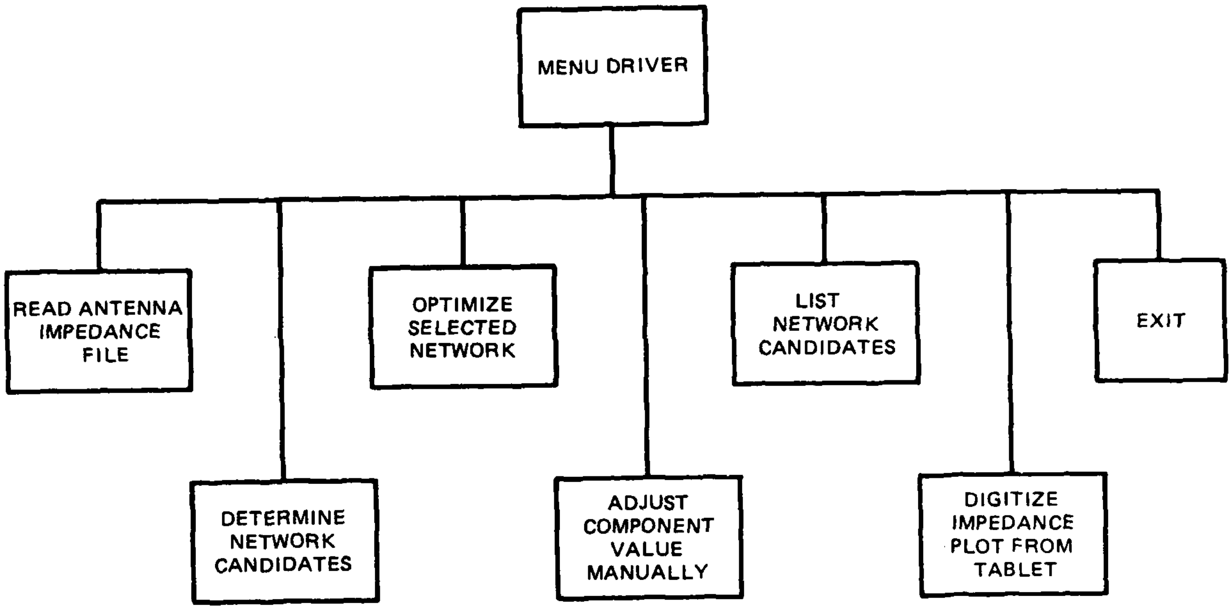


Figure 4-1. Structure of ANTMAT program.

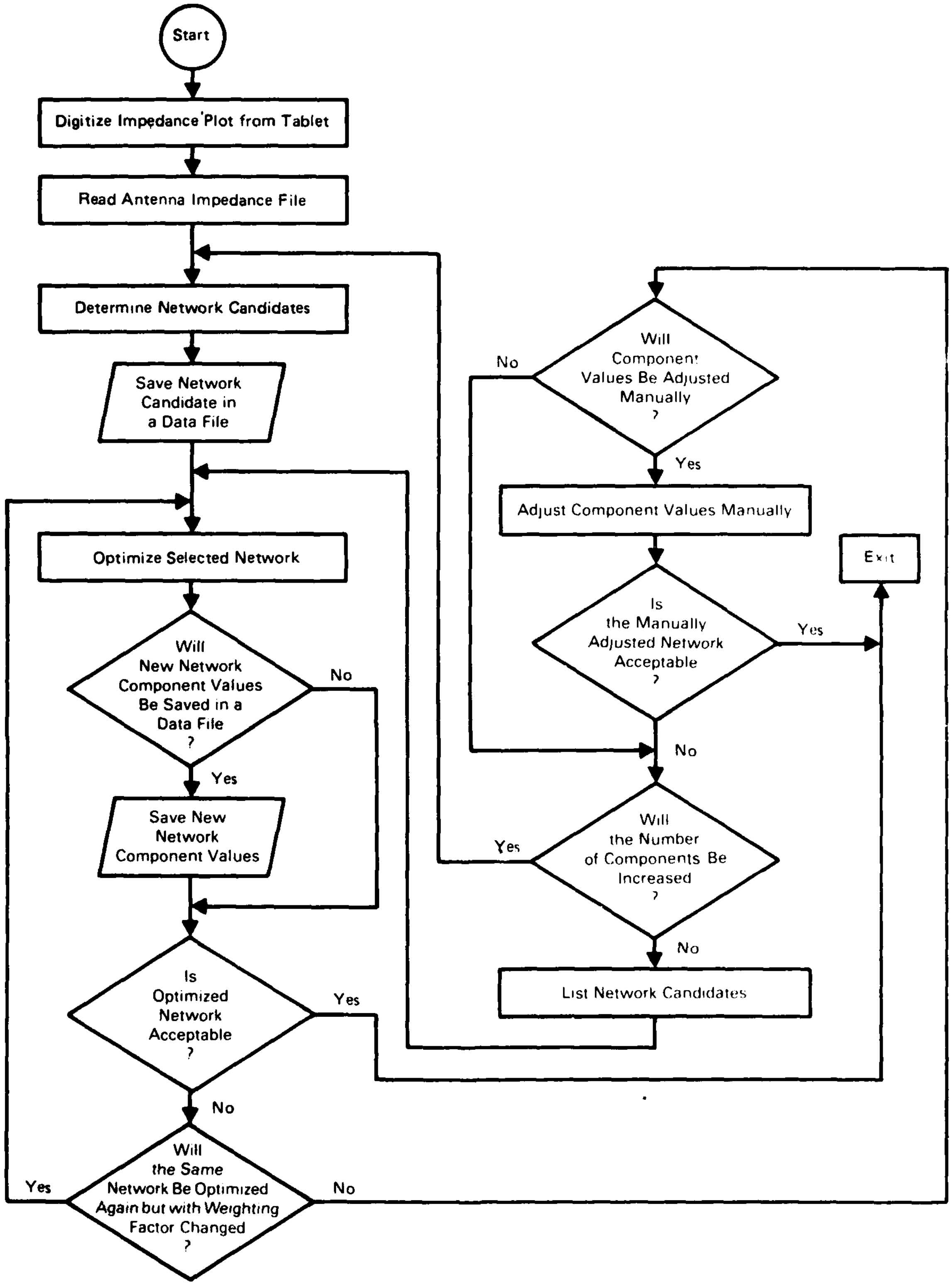


Figure 4-2. A sequence of operations for using ANTMAT program

4.2 HARDWARE AND SOFTWARE REQUIREMENTS

Hardware and software requirements for using the ANTMAT program are listed below:

Hardware requirements are:

1. Zenith 248-AT microcomputer with math co-processor and EGA color monitor by Zenith Data Systems or any IBM AT equivalent.
2. ThinkJet printer (Centronic parallel interface) by Hewlett-Packard.
3. SummaSketch 12-by 12-in. MM1201 graphics tablet (RS-232 serial interface) by Summagraphics Corporation.
4. HP 7470 (two-pen plotter) or HP 7475A (six-pen) plotter (RS-232 serial interface) by Hewlett-Packard.

Software requirements are:

1. Microsoft MS-DOS version 3.0 by Zenith Data Systems.
2. Microsoft QuickBASIC Compiler version 3.0 by Microsoft Corporation.

Special notes:

1. ThinkJet printer is connected to lpt1.
2. HP plotter is connected to com2 with 9600 baud.
3. SummaSketch graphics tablet is connected to com1 with 9600 baud, report format of the tablet is set up with MM ASCII BCD format, hand-held device is the 4 button cursor.
4. HP plotter paper can be blank 8-1/2 by 11 in. or IMPEDANCE DIAGRAM (SMITH) NOSC-SD 3900/22 (10-84) as shown in Figure A-1.

4.3 READ ANTENNA IMPEDANCE FILE

This function enables the ANTMAT program to read an existing antenna impedance file. The existing antenna impedance file, identified by a file name, has been established either by keyboard inputs through an editor or by using the "digitize impedance plot from tablet" function, which will be discussed in section 4.8. The antenna impedance file provides the following data: a number of antenna impedances, a table of frequency versus normalized antenna impedance values, and the impedance normalization constant. Based on

these antenna impedance values, the program calculates initial VSWR at each frequency.

4.4 DETERMINE NETWORK CANDIDATES

This section discusses the determination of a list of network candidates from which a network topology and initial component values are obtained by using the ANTMAT program. The network topology is either a pi network or a T network. If the "determine network candidates" function is selected before the "read antenna impedance file" function, the ANTMAT program will ask the user to input antenna impedances.

As pointed out in section 2.2, a network should consist of as few components as possible to minimize losses. The fewer the components in a given design, the more efficient will be the resulting network. The number of network components ranges from one component to six components. This is because:

1. There are three branches in either a pi network or a T network (see Figures 3-2 and 3-3).

2. There are six possible types of elements in a branch. Each element may consist of zero components (such as short-series element and open-parallel element), or one component (such as L element and C element), or two components (such as LCS element and LCP element) as depicted in Figure 3-4. Table 4-1 shows all possible pi networks and T networks having one through six network components.

The ANTMAT program inquires as to the number of network components. The program will investigate all possible networks which have the specified number of network components as shown in Table 4-1. For each of these possible networks, ANTMAT uses the optimization algorithm described in section 3 to find the component values that minimize the input reflection coefficient. The initial component values used for the optimization are 6.125 μH for inductors and 1275 pF for capacitors, which are the middle points within the practical range of component values. The number of iterations for the optimization process is set between 30 and 60 for speeding up the process. However, the user can override these preset values. The exponential weighting function option with an exponent of 1.02 is used in this determination of network topology procedure. The program then calculates impedance and VSWR with

Table 4-1. A list of network candidates.

NETWORK SEQUENCE	NETWORK TYPE	FIRST BRANCH ELEMENT TYPE	SECOND BRANCH ELEMENT TYPE	THIRD BRANCH ELEMENT TYPE	NUMBER OF COMPONENTS
1	T	SS	L	SS	1
2	T	SS	C	SS	1
3	T	SS	OP	L	1
4	T	SS	OP	C	1
5	T	SS	L	L	2
6	T	SS	L	C	2
7	T	SS	C	L	2
8	T	SS	C	C	2
9	T	SS	OP	LCS	2
10	T	SS	LCP	SS	2
11	T	L	L	SS	2
12	T	L	C	SS	2
13	T	C	L	SS	2
14	T	C	C	SS	2
15	T	SS	L	LCS	3
16	T	SS	C	LCS	3
17	T	SS	LCP	L	3
18	T	SS	LCP	C	3
19	T	L	L	L	3
20	T	L	L	C	3
21	T	L	C	L	3
22	T	L	C	C	3
23	T	L	LCP	SS	3
24	T	C	L	L	3
25	T	C	L	C	3
26	T	C	C	L	3
27	T	C	C	C	3
28	T	C	LCP	SS	3
29	T	LCS	L	SS	3
30	T	LCS	C	SS	3
31	PI	L	L	L	3
32	PI	L	L	C	3
33	PI	L	C	L	3
34	PI	L	C	C	3
35	PI	C	L	L	3
36	PI	C	L	C	3
37	PI	C	C	L	3
38	PI	C	C	C	3
39	T	SS	LCP	LCS	4
40	T	L	L	LCS	4
41	T	L	C	LCS	4
42	T	L	LCP	L	4
43	T	L	LCP	C	4
44	T	C	L	LCS	4
45	T	C	C	LCS	4
46	T	C	LCP	L	4

Table 4-1. A list of network candidates (continued).

NETWORK SEQUENCE	NETWORK TYPE	FIRST BRANCH ELEMENT TYPE	SECOND BRANCH ELEMENT TYPE	THIRD BRANCH ELEMENT TYPE	NUMBER OF COMPONENTS
47	T	C	LCP	C	4
48	T	LCS	L	L	4
49	T	LCS	L	C	4
50	T	LCS	C	L	4
51	T	LCS	C	C	4
52	T	LCS	LCP	SS	4
53	PI	L	L	LCP	4
54	PI	L	C	LCP	4
55	PI	L	LCS	L	4
56	PI	L	LCS	C	4
57	PI	C	L	LCP	4
58	PI	C	C	LCP	4
59	PI	C	LCS	L	4
60	PI	C	LCS	C	4
61	PI	LCP	L	L	4
62	PI	LCP	L	C	4
63	PI	LCP	C	L	4
64	PI	LCP	C	C	4
65	T	L	LCP	LCS	5
66	T	C	LCP	LCS	5
67	T	LCS	L	LCS	5
68	T	LCS	C	LCS	5
69	T	LCS	LCP	L	5
70	T	LCS	LCP	C	5
71	PI	L	LCS	LCP	5
72	PI	C	LCS	LCP	5
73	PI	LCP	L	LCP	5
74	PI	LCP	C	LCP	5
75	PI	LCP	LCS	L	5
76	PI	LCP	LCS	C	5
77	T	LCP	LCS	LCS	6
78	PI	LCP	LCS	LCP	6

matching network at each frequency. For each and every possible network with the specified number of network components, the ANTMAT calculates the mean (m) and standard deviation (σ) of VSWR and ranks these possible networks according to the following ranking factor (RF):

$$RF = m + 3\sigma \quad (4\text{-}1)$$

The network with the lowest value of RF is ranked as the first choice among the network candidates. A network with a negative component value will not be considered as a candidate. A network with a component value outside the practical range is ranked as a candidate with caution (a question mark is shown). The ranked network candidates can be saved in a data file which can be recalled by using the "list network candidates" command. Usually a few top ranked networks will be selected for further consideration. The network topology and the component values which are obtained by using this "determine network candidates" command will be considered as inputs to execute the next "optimize selected network" command. Figure 4-3 shows the procedure of the determination of network candidates.

4.5 OPTIMIZE THE SELECTED NETWORK

Upon the completion of "determine network candidates" command, there exists a list of network candidates with initial component values available to the user. The user will select a network from the list for further optimization (see Figure 4-4). The same optimization algorithm described in section 3 will be used. However, a weighting function which is different from the exponential weighting function can be employed. These weighting functions are discussed in section 3.4. Usually at this stage of the design, the around-the-average weighting function will be used. The number of iterations for the optimization process is increased from between 30 and 60 to between 100 and 200.

When the optimization algorithm finds new network component values for a specified weighting function, the user should decide whether these component values are acceptable and are to be saved in a disk file for future use. If the component values are not acceptable, the user should return to menu driver and select an appropriate command to continue the design of a matching network.

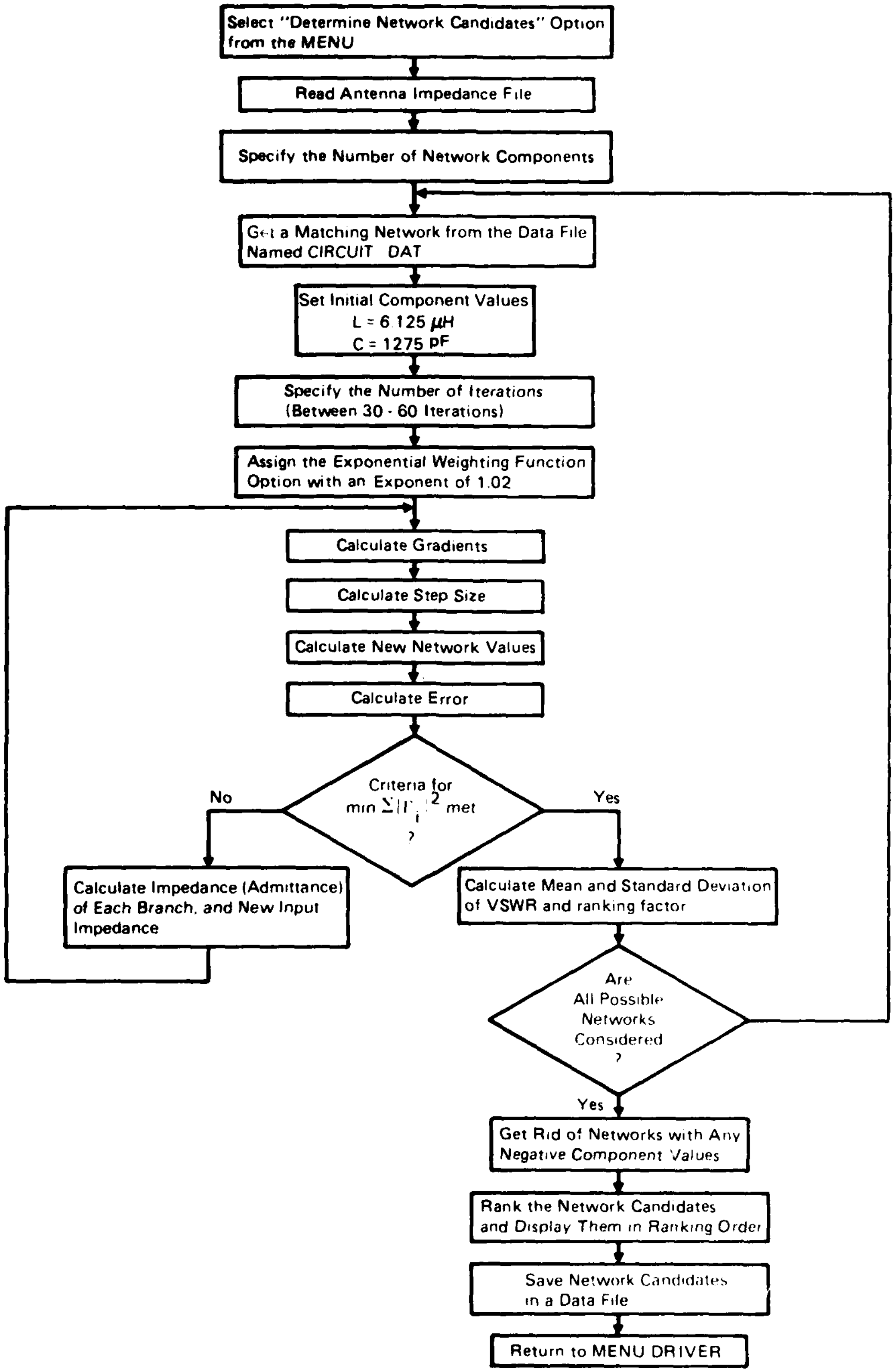


Figure 4-3. Determination of network candidates

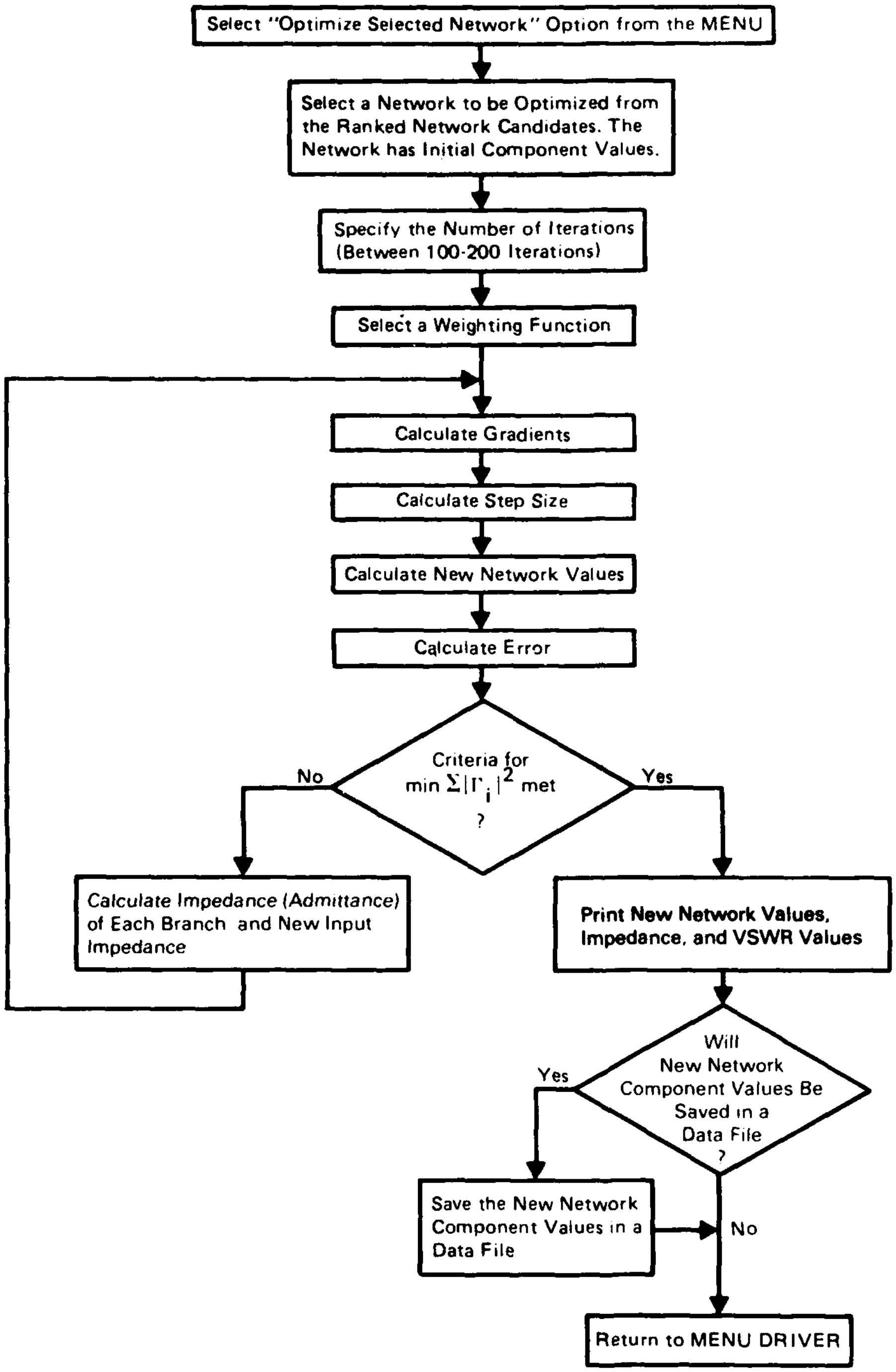


Figure 4-4. Optimization of the selected network.

The user can take one of the following options:

1. The "optimize selected network" command should be selected if the user decides that the same network will be optimized again but with different weighting factors.

2. The "adjust component values manually" command should be selected if the user decides that the component values will be adjusted manually.

3. The "list network candidate" command should be selected if the user decides that a new network will be selected from the network candidates which are saved in a disk file previously.

4. The "determine network candidates" command should be selected if the user decides that a new list of network candidates will be generated by varying the number of components.

Of course, if the component values are acceptable, the user should return to menu driver and select the "exit" command to stop the design process.

4.6 ADJUST COMPONENT VALUE MANUALLY

If the optimized network is not acceptable, the "adjust component value manually" command allows the user to change component values manually.

4.7 LIST NETWORK CANDIDATES

If the optimized network is not acceptable and the user does not like to adjust the component values manually, the user may employ the "list network candidates" command to get a list of network candidates for the specified number of network components. Then the user can select another network from the list and try to optimize again by using the "optimize selected network" command. If no listed network candidate is acceptable, then the user should consider increasing the number of network components and use the "determine network candidates" command to find new network candidates. The design process shown in Figure 4-1 can be repeated until the number of network components reaches six. If an acceptable matching network is obtained, the user will use the "exit" command to terminate the design process. Otherwise, the user should consider the following options:

1. Redesign the antenna such that a matching network can be obtained to meet the VSWR requirement.

2. Relax the VSWR requirement and accept the best matching network available.

4.8 DIGITIZE IMPEDANCE PLOT FROM TABLET

This function creates an antenna impedance file in a computer by using a digitizer to read antenna impedances for various frequencies plotted on a Smith Chart. The frequencies are in megahertz and the antenna impedances are normalized with 50 + j0 ohms. The impedances are entered according to the ascending order of frequencies. An algorithm to perform the function is presented in this section.

A Smith Chart showing antenna impedance plot is put on a digitizer tablet. Two points are required to define the orientation (bearing angle) of the Smith Chart with respect to the digitizer tablet. The infinite-resistance point of the Smith Chart is chosen to be the first point (x_1, y_1) and is located at the bottom of the tablet. The zero-resistance point is the second point (x_2, y_2) and is located at the top of the tablet. The coordinates of these two points, (x_1, y_1) and (x_2, y_2), are in digitizer tablet units. The resolution of the digitizer tablet is set at 500 x 500 lines per inch. It is required that the straight line connecting these two points must be a vertical line ($\theta = 0$) as shown in Figure 4-5. However, this straight line is usually not a vertical line and requires a rotation of angle θ, using (x_1, y_1) as the pivot point. The bearing angle θ can be calculatd by using Equation (4-2).

$$\sin\theta = \frac{x_2 - x_1}{\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}} . \tag{4-2}$$

After the rotation of angle θ, point (x_2,y_2) becomes (x_d,y_d) as given in Equation (4-3).

$$\begin{cases} x_d = x_1 + (x_2 - x_1)\cos\theta - (y_2 - y_1)\sin\theta \\ \quad = x_1 \\ y_d = y_1 + (y_2 - y_1)\cos\theta + (x_2 - x_1)\sin\theta . \end{cases} \tag{4-3}$$

The outside circle of the Smith Chart shown in Figure 4-5 can be considered as a circle with unit radius centered at a new origin 0' with new axes x',y' as it is shown in Figure 4-6. The new origin 0' is located at $(x_1, (y_d + y_1)/2)$

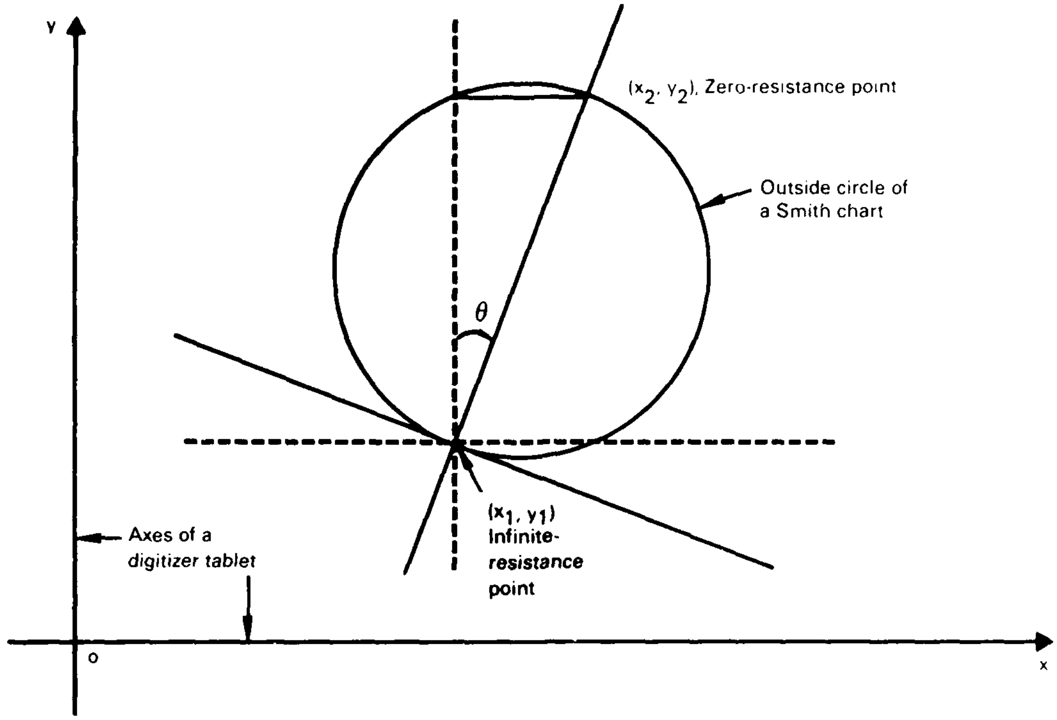


Figure 4-5. The orientation (bearing angle) of a Smith Chart with respect to digitized tablet.

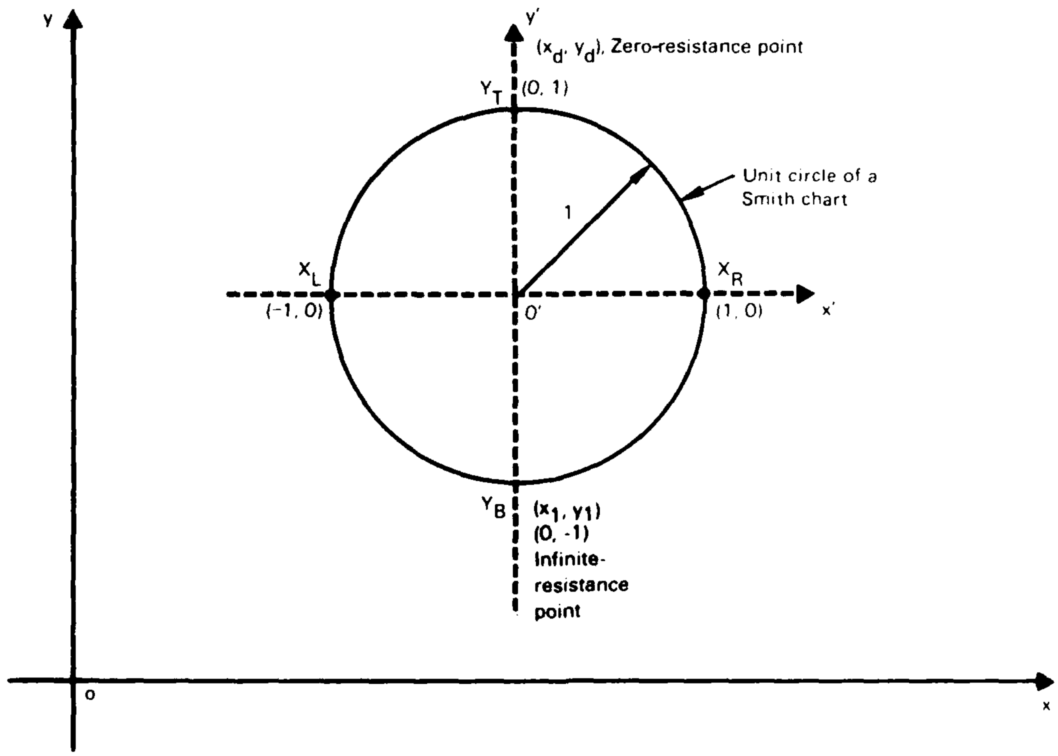


Figure 4-6. Translation and scaling of digitizer axes.

with respect to the x,y axes. The boundaries Y_T, Y_B, X_L, X_R (top, bottom, left and right) of the unit circle are (0, 1), (0, -1), (-1, 0), and (1, 0), respectively, with respect to the new x',y' axes. The transformation from x,y axes to x',y' axes requires translation and scaling as given in Equation (4-4)

$$\begin{cases} x' = \frac{1}{s}(x - x_1) \\ y' = \frac{1}{s}\left(y - \frac{y_d + y_1}{2}\right) , \end{cases} \tag{4-4}$$

where scaling factor s is

$$s = \frac{y_d - y_1}{2} .$$

Axes x' and y' are rotated 90 deg counterclockwise so that the zero-resistance point is located on the left-hand side instead of at the top. The new axes are called x" and y" and are shown in figure 4-7.

$$\begin{cases} x'' = -y' \\ y'' = x' \end{cases} \tag{4-5}$$

The purpose of this rotation of axes is to orient the axes in the directions suitable for a conformed transformation to be performed next. A conformal transformation

$$z = \frac{1 + W}{1 - W} \tag{4-6}$$

is to transform the rectangular coordinate axes into orthogonal circular coordinate curves (the Smith Chart), where $W = u + jv$ is a complex number representing impedance on a retangular chart, and $z = r + jx$ is a complex number representing impedance on a circular chart (the Smith Chart). Figure 4-8 shows these two sets of coordinate axes. Using Equation (4-6), we can calculate:

$$\gamma = \frac{1 - u^2 + v^2}{(1 - \mu)^2 + v^2} \tag{4-7}$$

$$x = \frac{2v}{(1 - u)^2 + v^2} \tag{4-8}$$

where $u = x''$ and $v = y''$.

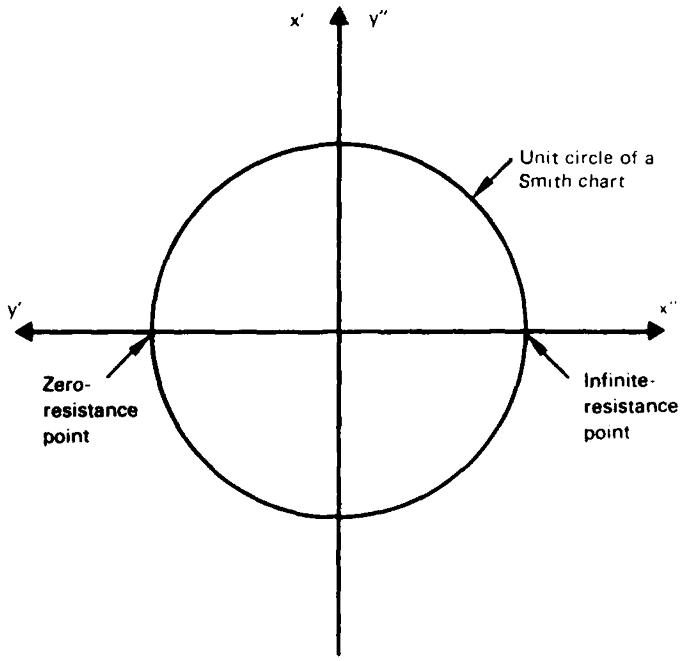


Figure 4-7. Rotation of x' and y' axes such that zero-resistance point is located at the left-hand side.

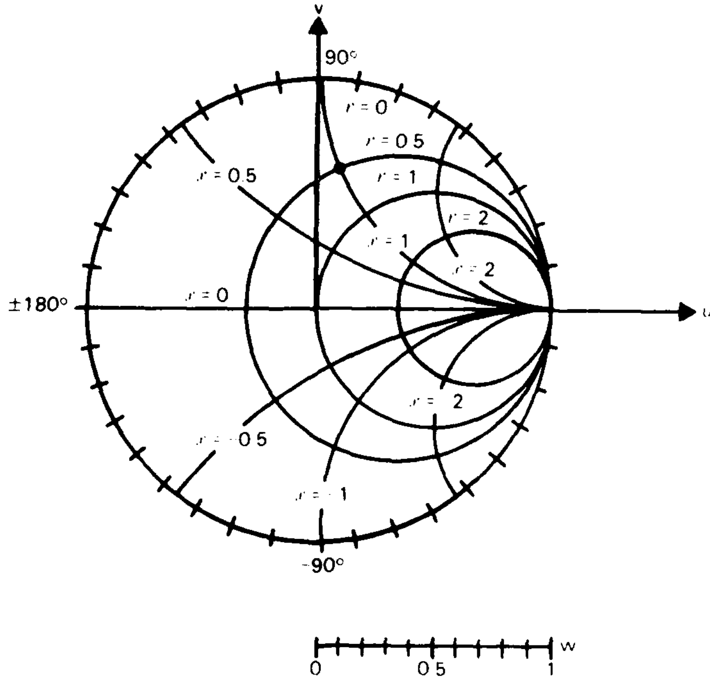


Figure 4-8. A conformal transformation which transforms the rectangular coordinates into orthogonal circular coordinates.

5.0 A SAMPLE DESIGN PROBLEM

A sample design problem is given in this chapter to illustrate the design procedure and the use of the ANTMAT program described in section 4. The problem is to design a broadband matching network for the broadband HF antenna of Figure 5-1. The goal is a broadband matching network to provide a maximum VSWR of 3:1 over the operating band from 2 to 6 MHz. In this sample problem there are impedance data at 21 frequencies. The impedance values are normalized to 50 + j0 ohms.

At first, the ANTMAT program asks which HP plotter will be used. HP 2 stands for Hewlett-Packard two-pen plotter, model number HP 7470. HP 6 stands for Hewlett-Packard six-pen plotter, model number HP 7475A.

5.1 CREATE AN IMPEDANCE FILE

An antenna impedance file can be created in a computer either by using the "digitize impedance plot from tablet" function or by keyboard inputs through an editor. This sample problem uses the "digitize impedance plot from tablet" function. This function is selected from the menu (selection 6). A digitizer is used to read 21 antenna impedances plotted on the Smith Chart shown in Figure 5-1. The name of the antenna impedance file is SAMP1.IMP. After the impedance file is created, the "exit" function is selected (selection 7) for returning to the menu driver. A sample printout is given as follows:

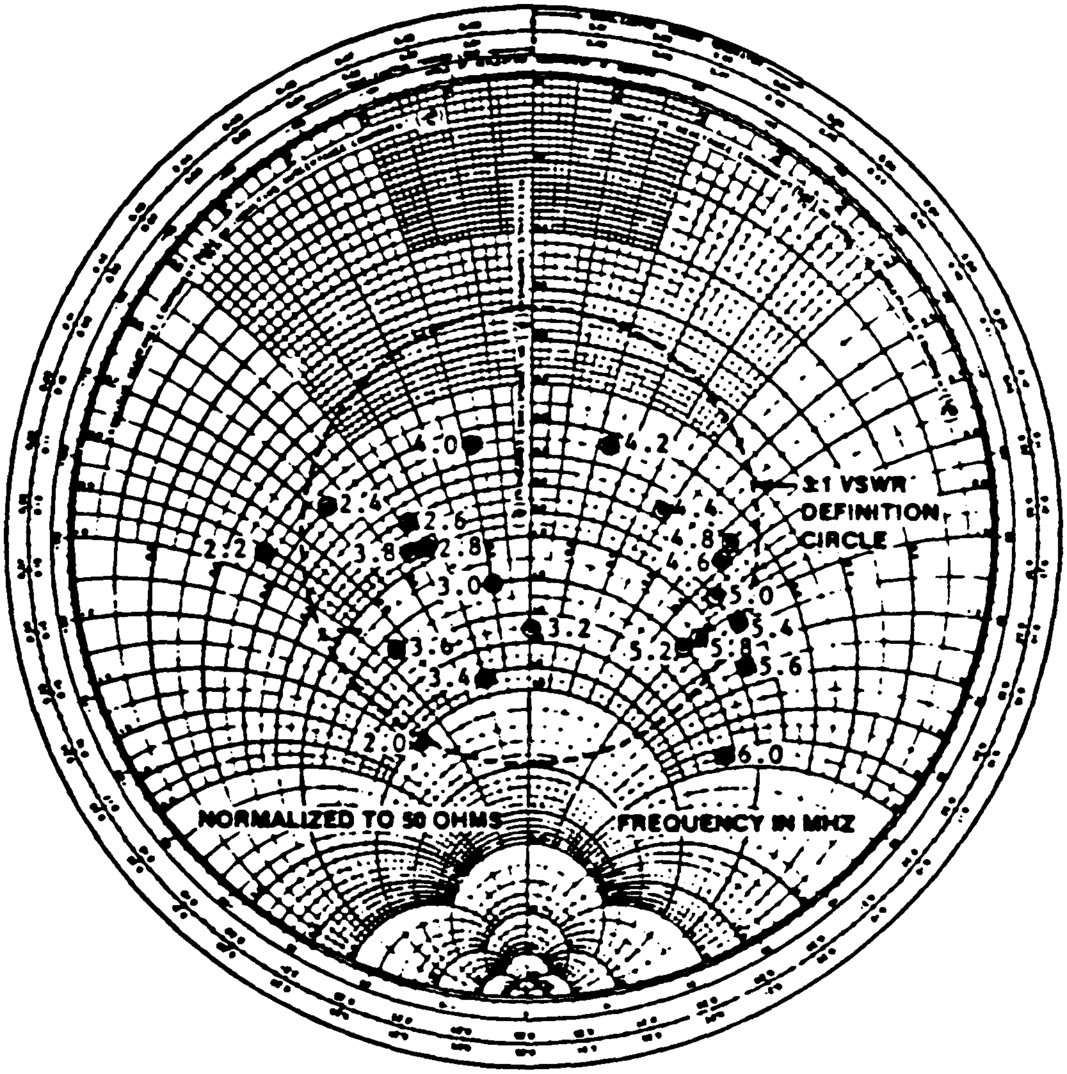


Figure 5-1. Impedance points of a broadband antenna.

```
HP PLOTTER TYPE: 2 PENS OR 6 PENS -- (HP2 / HP6) ? HP6
        MENU
1 - LOAD ANTENNA IMPEDANCE FILE
2 - DETERMINE NETWORK CANDIDATES
3 - OPTIMIZE SELECTED NETWORK
4 - ADJUST COMPONENT VALUE MANUALLY
5 - LIST NETWORK CANDIDATES
6 - DIGITIZE IMPEDANCE PLOT FROM TABLET
7 - EXIT
SELECTION (1-7) ? 6

ORIENTATION OF SMITH CHART - INFINITY ON BOTTOM, ZERO ON TOP
FREQUENCY IN MHZ AND IMPEDANCE MUST BE NORMALIZED WITH 50 OHMS

ENTER INFINITY POINT USING BUTTON 1
ENTER ZERO POINT USING BUTTON 1
EQUAL FREQUENCY STEPPING ( STEP SIZE IN MHZ / N) ? .2
ENTER STARTING FREQUENCY IN MHZ ? 2
PRESS BUTTON 1 FOR INPUT, 2 FOR STOP ? R =  2.07  X = -1.27  F =  2.00
PRESS BUTTON 1 FOR INPUT, 2 FOR STOP ? R =  0.54  X = -0.93  F =  2.20
PRESS BUTTON 1 FOR INPUT, 2 FOR STOP ? R =  0.62  X = -0.67  F =  2.40
PRESS BUTTON 1 FOR INPUT, 2 FOR STOP ? R =  0.83  X = -0.47  F =  2.60
PRESS BUTTON 1 FOR INPUT, 2 FOR STOP ? R =  0.96  X = -0.45  F =  2.80
PRESS BUTTON 1 FOR INPUT, 2 FOR STOP ? R =  1.21  X = -0.20  F =  3.00
PRESS BUTTON 1 FOR INPUT, 2 FOR STOP ? R =  1.51  X =  0.01  F =  3.20
PRESS BUTTON 1 FOR INPUT, 2 FOR STOP ? R =  1.86  X = -0.39  F =  3.40
PRESS BUTTON 1 FOR INPUT, 2 FOR STOP ? R =  1.33  X = -0.90  F =  3.60
PRESS BUTTON 1 FOR INPUT, 2 FOR STOP ? R =  0.93  X = -0.54  F =  3.80
PRESS BUTTON 1 FOR INPUT, 2 FOR STOP ? R =  0.66  X = -0.18  F =  4.00
PRESS BUTTON 1 FOR INPUT, 2 FOR STOP ? R =  0.65  X =  0.24  F =  4.20
PRESS BUTTON 1 FOR INPUT, 2 FOR STOP ? R =  0.77  X =  0.49  F =  4.40
PRESS BUTTON 1 FOR INPUT, 2 FOR STOP ? R =  0.78  X =  0.79  F =  4.60
PRESS BUTTON 1 FOR INPUT, 2 FOR STOP ? R =  0.71  X =  0.75  F =  4.80
PRESS BUTTON 1 FOR INPUT, 2 FOR STOP ? R =  0.89  X =  0.89  F =  5.00
PRESS BUTTON 1 FOR INPUT, 2 FOR STOP ? R =  1.21  X =  0.99  F =  5.20
PRESS BUTTON 1 FOR INPUT, 2 FOR STOP ? R =  0.88  X =  1.06  F =  5.40
PRESS BUTTON 1 FOR INPUT, 2 FOR STOP ? R =  0.95  X =  1.30  F =  5.60
PRESS BUTTON 1 FOR INPUT, 2 FOR STOP ? R =  1.12  X =  1.01  F =  5.80
PRESS BUTTON 1 FOR INPUT, 2 FOR STOP ? R =  1.33  X =  1.92  F =  6.00
PRESS BUTTON 1 FOR INPUT, 2 FOR STOP ?
ENTER FILE NAME FOR DATA STORAGE = ? SAMP1.IMP
ENTER COMMENT = ? DIGITIZED DATA FROM FIGURE 5-1

IMPEDANCE POINTS =   21.0

     FREQ      R       X

     2.00     2.07    -1.27
     2.20     0.54    -0.93
     2.40     0.62    -0.67
     2.60     0.83    -0.47
     2.80     0.96    -0.45
     3.00     1.21    -0.20
     3.20     1.51     0.01
     3.40     1.86    -0.39
```

```
3.60      1.33     -0.90
3.80      0.93     -0.54
4.00      0.66     -0.18
4.20      0.65      0.24
4.40      0.77      0.49
4.60      0.78      0.79
4.80      0.71      0.75
5.00      0.89      0.89
5.20      1.21      0.99
5.40      0.88      1.06
5.60      0.95      1.30
5.80      1.12      1.01
6.00      1.33      1.92

          MENU
1 - LOAD ANTENNA IMPEDANCE FILE
2 - DETERMINE NETWORK CANDIDATES
3 - OPTIMIZE SELECTED NETWORK
4 - ADJUST COMPONENT VALUE MANUALLY
5 - LIST NETWORK CANDIDATES
6 - DIGITIZE IMPEDANCE PLOT FROM TABLET
7 - EXIT
SELECTION (1-7) ? 7
```

5.2 DETERMINE NETWORK CANDIDATES HAVING ONE COMPONENT

When the "determine network candidate" function is slected from the menu (selection 2), at first the ANTMAT program will automatically load the antenna impedance file. Then it will find network candidates which have the specified number of components.

First, the program inquires whether the impedances stored in the impendance file are normalized and asks the name of the impedance file. In this sample problem, the impedance is normalized, and the impedance file is called SAMP1.IMP. The impedance, together with the Smith Chart, can be displayed on the screen of a color monitor and/or plotted by a Hewlett-Packard plotter. A sample printout is given as follows:

HP PLOTTER TYPE: 2 PENS OR 6 PENS -- (HP2 / HP6) ? HP6

MENU

1 - LOAD ANTENNA IMPEDANCE FILE
2 - DETERMINE NETWORK CANDIDATES
3 - OPTIMIZE SELECTED NETWORK
4 - ADJUST COMPONENT VALUE MANUALLY
5 - LIST NETWORK CANDIDATES
6 - DIGITIZE IMPEDANCE PLOT FROM TABLET
7 - EXIT

SELECTION (1-7) ? 2

IMPEDANCE INPUT

IMPEDANCE IS NORMALIZED (Y/N) ? Y

IMPEDANCE FILE ? SAMP1.IMP

IMPEDANCE DATA

NUMBER	FREQ (MHZ)	RESISTANCE	REACTANCE	VSWR
1	2	2.07	-1.27	2.998804
2	2.2	.54	- .93	3.725066
3	2.4	.62	- .67	2.567443
4	2.6	.83	- .4	1.719348
5	2.8	.96	- .45	1.579487
6	3	1.21	- .2	1.300669
7	3.2	1.51	.01	1.510118
8	3.4	1.86	- .39	1.972416
9	3.6	1.33	- .9	2.245584
10	3.8	.93	- .54	1.746119
11	4	.60	- .18	1.598756
12	4.2	.65	.24	1.682845
13	4.4	.77	.49	1.835797
14	4.6	.78	.79	2.454817
15	4.8	.71	.75	2.512731
16	5	.89	.89	2.504279
17	5.2	1.21	.99	2.435924
18	5.4	.88	1.06	2.954742
19	5.6	.95	1.3	3.495497
20	5.8	1.12	1.01	2.528108
21	6	1.33	1.92	4.637999

DISPLAY SMITH CHART (Y/N)? N

OUTPUT TO HP PLOTTER (Y/N) ? N

The next step is to find network candidates having one component. The optimization algorithm discussed in section 3.1 uses 30 to 60 iterations to determine network candidates. Four networks (network numbers 1, 2, 3, and 4 as shown in Table 4-1) have been evaluated. The results show that three of them are network candidates (networks numbered 2, 4, and 1). Among the three candidates, network number 2 is the best. Network number 4 and network number 1 are cautioned with a "?" mark, which means that the component values are outside the practical range for shipboard application in the HF frequency band as discussed in section 2.2. The network number 2 is a T network with the first and the third branch elements being short-series, and a capacitor of 170.7828 pF as the second branch element. In other words, the network number 2 is just a parallel capacitor. The list of network candidates is saved in a library file called NET1.LIB for future use. The "exit" function is selected for returning to the menu driver. A sample printout is given as follows:

```
       NETWORK
NUMBER OF NETWORK COMPONENTS (1-6) ? 1
UPPER LIMIT ON ITERATIONS =  60    ?
LOWER LIMIT ON ITERATIONS =  30    ?
EVALUATED NETWORK  1
EVALUATED NETWORK  2
EVALUATED NETWORK  3
EVALUATED NETWORK  4
  NETWORK RESULTS

NET =     2      4      1
 FREQ   VSWR   VSWR   VSWR
 2.00   3.2    3.0    2.9
 2.20   4.2    3.7    2.9
 2.40   2.9    2.6    2.1
 2.60   2.0    1.7    1.4
 2.80   1.8    1.6    1.3
 3.00   1.5    1.3    1.3
 3.20   1.6    1.5    1.6
 3.40   2.2    2.0    1.9
 3.60   2.6    2.2    2.0
 3.80   2.1    1.7    1.5
 4.00   1.8    1.6    1.5
 4.20   1.5    1.7    1.8
 4.40   1.5    1.8    2.1
 4.60   1.9    2.5    2.8
 4.80   2.0    2.5    2.8
 5.00   2.0    2.5    2.8
 5.20   2.1    2.4    2.7
 5.40   2.4    3.0    3.2
 5.60   2.9    3.5    3.8
 5.80   2.1    2.5    2.7
 6.00   4.1    4.6    4.9
```

```
(NETWORKS RANKED FROM BEST TO WORST)

  2 T-SS-C-SS   =170.7828 :
? 4 T-SS-OP-C   =6.953396E+09 :
? 1 T-SS-L-SS   =14.89855 :
 SAVE TO FILE   ? NETWORK1.LIB

      MENU
1 - LOAD ANTENNA IMPEDANCE FILE
2 - DETERMINE NETWORK CANDIDATES
3 - OPTIMIZE SELECTED NETWORK
4 - ADJUST COMPONENT VALUE MANUALLY
5 - LIST NETWORK CANDIDATES
6 - DIGITIZE IMPEDANCE PLOT FROM TABLET 7 - EXIT
7 - EXIT
SELECTION (1-7) ? 7
```

5.3 OPTIMIZE THE SELECTED NETWORK HAVING ONE COMPONENT

A list of network candidates having one component has been saved in the file named NETWORK1.LIB. If the user remembers what these network candidates are and has decided which of the network candidates is chosen for optimization, then he should select the "optimize selected network" function from the menu (selection 3) to start optimizing the chosen network. Otherwise, he may select first the "list network candidates" function from the menu (selection 5) to review these network candidates, followed by the selection of the "optimize selected network" function. Another possibility is that the user may wish to select the "load antenna impedance file" function from the menu (selection 1) for the review of antenna impedance files (SAMP1.IMP) prior to the reselection of "list network candidates" function. In summary, there are three possibilities:

1. The selection of "optimize selected network" function.
2. The selection of "list network candidates" function, followed by the selection of "optimize selected network" function.
3. The selection of "load antenna impedance file" function first, then the selection of "list network candidates" function, followed by the selection of "optimize selected network" function.

This sample problem selects the third possibility for illustration. During the process of illustrating the third possibility, in reality, the first and the second possibilities are also illustrated.

When the "load antenna impedance file" function is selected from the menu (selection 1), the program inquires whether the impedances stored in the impedance file are normalized and asks the name of the impedance file. The impedances, along with the Smith Chart, can be displayed on the screen and/or plotted by a plotter. A sample printout is given as follows:

```
HP PLOTTER TYPE: 2 PENS OR 6 PENS -- (HP2 / HP6) ? HP6
        MENU
1 - LOAD ANTENNA IMPEDANCE FILE
2 - DETERMINE NETWORK CANDIDATES
3 - OPTIMIZE SELECTED NETWORK
4 - ADJUST COMPONENT VALUE MANUALLY
5 - LIST NETWORK CANDIDATES
6 - DIGITIZE IMPEDANCE PLOT FROM TABLET
7 - EXIT
SELECTION (1-7) ? 1
  IMPEDANCE INPUT
IMPEDANCE IS NORMALIZED (Y/N) ? Y
IMPEDANCE FILE                ? SAMP1.IMP
  IMPEDANCE DATA

NUMBER        FREQ (MHZ)    RESISTANCE    REACTANCE     VSWR

1             2             2.07          -1.27         2.998804
2             2.2            .54          - .93         3.725066
3             2.4            .62          - .67         2.567443
4             2.6            .83          - .47         1.719348
5             2.8            .96          - .45         1.579487
6             3             1.21          - .2          1.300669
7             3.2           1.51            .01         1.510118
8             3.4           1.86          - .39         1.972416
9             3.6           1.33          - .9          2.245584
10            3.8            .93          - .54         1.746119
11            4              .66          - .18         1.598756
12            4.2            .65            .24         1.682845
13            4.4            .77            .49         1.835797
14            4.6            .78            .79         2.454817
15            4.8            .71            .75         2.512731
16            5              .89            .89         2.504279
17            5.2           1.21            .99         2.435924
18            5.4            .88           1.06         2.954742
19            5.6            .95           1.3          3.495497
20            5.8           1.12           1.01         2.528108
21            6             1.33           1.92         4.637999

DISPLAY SMITH CHART (Y/N)? N

OUTPUT TO HP PLOTTER  (Y/N) ? N
```

When the "list network candidates" function is selected (selection 5), the program asks the file name of the network candidates and which of the following options will be executed:

L: Load the network candidates file from a diskette to the computer memory and show all network candidates on the screen.

A: Show all network candidates on the screen. The network candidates file has been saved in the computer memory.

#: Identify which network candidate (by its network number as shown in Table 4-1) will be optimized.

Q: Quit "list network candidates" function and return to the menu driver.

A sample printout is given as follows:

```
      MENU
1 - LOAD ANTENNA IMPEDANCE FILE
2 - DETERMINE NETWORK CANDIDATES
3 - OPTIMIZE SELECTED NETWORK
4 - ADJUST COMPONENT VALUE MANUALLY
5 - LIST NETWORK CANDIDATES
6 - DIGITIZE IMPEDANCE PLOT FROM TABLET
7 - EXIT
SELECTION (1-7) ? 5
    NETWORK LIST
NETWORK NUMBER [ L (OAD), A (LL), #, Q (UIT) ] ? L
FILE NAME =  ? NETWORK1.LIB
  2 T-SS-C-SS  =170.7828 :
? 4 T-SS-OP-C  =6.953396E+09 :
? 1 T-SS-L-SS  =14.89855 :
NETWORK NUMBER [ L (OAD), A (LL), #, Q (UIT) ] ? Q
```

When the "optimize selected network" function is selected (selection 3), the program asks which network candidate will be optimized, whether the impedances together with the Smith Chart will be displayed on the screen of a color monitor and/or plotted by a HP lotter, the upper and lower limits of the iterations which the optimization algorithm will perform, and the weighting functions to be used.

In this sample problem, the network number 2 is to be optimized. The impedances, along with the Smith Chart, will not be displayed or plotted. The optimization algorithm discussed in section 3.1 uses 100 to 200 iterations to

optimize the component value. The around-the-average weighting function is used. The first and the second multipliers for the average weighting function as described in Equation (3-31) are chosen to be 5 and 1, respectively. However, after the optimization, the network number 2 does not provide a maximum VSWR of 3:1 over the operating band from 2 to 6 MHz. The results are given below:

```
        MENU
1 - LOAD ANTENNA IMPEDANCE FILE
2 - DETERMINE NETWORK CANDIDATES
3 - OPTIMIZE SELECTED NETWORK
4 - ADJUST COMPONENT VALUE MANUALLY
5 - LIST NETWORK CANDIDATES
6 - DIGITIZE IMPEDANCE PLOT FROM TABLET
7 - EXIT
SELECTION (1-7) ? 3
    OPTIMIZATION
NETWORK TO BE OPTIMIZED ? 2
T NETWORK CONFIGURATION:
COMPONENT NO.  1  SHORT CIRCUIT SERIES
COMPONENT NO.  2  CAPACITOR
 170.7828  PICOFARADS
COMPONENT NO.  3  SHORT CIRCUIT SERIES
DISPLAY SMITH CHART (Y/N)? N

OUTPUT TO HP PLOTTER  (Y/N) ? N
UPPER LIMIT ON ITERATIONS =  200   ?
LOWER LIMIT ON ITERATIONS =  100   ?
1 - EXPONENTIAL WEIGHTING FUNCTION
2 - AROUND THE AVERAGE WEIGHTING FUNCTION
3 - USER INPUT WEIGHTS ON SELECTED FREQUENCIES
4 - WEIGHT IS 1 ON ALL FREQUENCY POINTS
SELECTION (1-4) ? 2
SECOND MULTIPLIER FOR AVERAGE WEIGHTING  =  1  ?
FIRST MULTIPLIER FOR AVERAGE WEIGHTING =  2  ? 5
```

FREQ (MHZ)	RESISTANCE	REACTANCE	VSWR	OLD-VSWR	WEIGHT
2	1.738582	-1.389555	3.1	3.2	5.4
2.2	.4739706	- .8890662	4.0	4.2	10.5
2.4	.558602	- .6623768	2.8	2.9	4.1
2.6	.764141	- .503684	1.9	2.0	1.0
2.8	.8795296	- .5062626	1.7	1.8	1.0
3	1.148564	- .3294421	1.4	1.5	1.0
3.2	1.47646	- .2227502	1.5	1.6	1.0
3.4	1.644879	- .6988254	2.1	2.2	1.0
3.6	1.066819	- .9646157	2.5	2.6	2.8
3.8	.8076454	- .5933422	2.0	2.1	1.0
4	.6256601	- .2284718	1.7	1.8	1.0
4.2	.6890769	.1847589	1.5	1.5	1.0
4.4	.8783991	.4227093	1.6	1.5	1.0
4.6	.9863108	.7653028	2.1	1.9	1.0
4.8	.8970956	.736807	2.2	2.0	1.0
5	1.183506	.8402107	2.2	2.0	1.0
5.2	1.647068	.7837378	2.2	2.1	1.0
5.4	1.283399	1.058747	2.5	2.4	1.3
5.6	1.552735	1.351424	3.0	2.9	3.8
5.8	1.601304	.8293129	2.2	2.1	1.0
6	2.905854	1.864146	4.2	4.1	10.1

```
DISPLAY SMITH CHART (Y/N)? N
```

```
OUTPUT TO HP PLOTTER  (Y/N) ? N
  NETWORK RESULTS
NET =     2
 FREQ   VSWR
 2.00    3.1
 2.20    4.0
 2.40    2.8
 2.60    1.9
 2.80    1.7
 3.00    1.4
 3.20    1.5
 3.40    2.1
 3.60    2.5
 3.80    2.0
 4.00    1.7
 4.20    1.5
 4.40    1.6
 4.60    2.1
 4.80    2.2
 5.00    2.2
 5.20    2.2
 5.40    2.5
 5.60    3.0
 5.80    2.2
 6.00    4.2

 (NETWORKS RANKED FROM BEST TO WORST)

   2 T-SS-C-SS   =103.7427 :
  SAVE TO FILE NETWORK1.LIB ?
```

We will try to optimize the same network (network number 2) again by putting more weights on the frequency points whose VSWRs are greater than the average VSWR value. The around-the-average weighting function is used with the first multiplier for the average weighting increased to 15. However, the results as shown below are still unacceptable. Therefore, we will increase the number of network components. In the next section, a new list of network candidates having two components will be generated.

```
          MENU
1 - LOAD ANTENNA IMPEDANCE FILE
2 - DETERMINE NETWORK CANDIDATES
3 - OPTIMIZE SELECTED NETWORK
4 - ADJUST COMPONENT VALUE MANUALLY
5 - LIST NETWORK CANDIDATES
6 - DIGITIZE IMPEDANCE PLOT FROM TABLET
7 - EXIT
SELECTION (1-7) ? 3
    OPTIMIZATION
NETWORK TO BE OPTIMIZED ? 2
T NETWORK CONFIGURATION:
COMPONENT NO.  1  SHORT CIRCUIT SERIES COMPONENT NO.  2  CAPACITOR
 103.7427  PICOFARADS
COMPONENT NO.  3  SHORT CIRCUIT SERIES
DISPLAY SMITH CHART (Y/N)? N

OUTPUT TO HP PLOTTER  (Y/N) ? N
UPPER LIMIT ON ITERATIONS =  200   ?
LOWER LIMIT ON ITERATIONS =  100   ?
1 - EXPONENTIAL WEIGHTING FUNCTION
2 - AROUND THE AVERAGE WEIGHTING FUNCTION
3 - USER INPUT WEIGHTS ON SELECTED FREQUENCIES
4 - WEIGHT IS 1 ON ALL FREQUENCY POINTS
SELECTION (1-4) ? 2
SECOND MULTIPLIER FOR AVERAGE WEIGHTING  =  1  ?
FIRST MULTIPLIER FOR AVERAGE WEIGHTING =  2  ? 15
```

FREQ (MHZ)	RESISTANCE	REACTANCE	VSWR	OLD-VSWR	WEIGHT
2	1.66802	-1.403637	3.1	3.1	13.0
2.2	.4604892	- .8798658	4.1	4.0	26.5
2.4	.5456095	- .6600205	2.8	2.8	8.0
2.6	.7493545	- .5097733	1.9	1.9	1.0
2.8	.8610466	- .5165563	1.8	1.7	1.0
3	1.131185	- .3557364	1.4	1.4	1.0
3.2	1.459204	- .2724308	1.6	1.5	1.0
3.4	1.585783	- .7513486	2.1	2.1	1.0
3.6	1.01315	- .9685288	2.5	2.5	3.5
3.8	.7809113	- .6010644	2.0	2.0	1.0
4	.6170563	- .2383076	1.8	1.7	1.0
4.2	.696751	.1707895	1.5	1.5	1.0
4.4	.9023761	.4023982	1.5	1.6	1.0
4.6	1.038653	.7499366	2.1	2.1	1.0
4.8	.9450485	.7256623	2.1	2.2	1.0
5	1.258253	.8102404	2.1	2.2	1.0
5.2	1.743836	.6939627	2.1	2.2	1.0
5.4	1.395527	1.030729	2.5	2.5	4.6
5.6	1.734756	1.313271	3.0	3.0	12.1
5.8	1.713205	.7376389	2.1	2.2	1.0
6	3.387876	1.555136	4.2	4.2	29.6

```
DISPLAY SMITH CHART (Y/N)? N
```

```
OUTPUT TO HP PLOTTER  (Y/N) ? N
  NETWORK RESULTS

NET =     2
 FREQ  VSWR
 2.00   3.1
 2.20   4.1
 2.40   2.8
 2.60   1.9
 2.80   1.8
 3.00   1.4
 3.20   1.6
 3.40   2.1
 3.60   2.5
 3.80   2.0
 4.00   1.8
 4.20   1.5
 4.40   1.5
 4.60   2.1
 4.80   2.1
 5.00   2.1
 5.20   2.1
 5.40   2.5
 5.60   3.0
 5.80   2.1
 6.00   4.2

(NETWORKS RANKED FROM BEST TO WORST)
  2 T-SS-C-SS  =127.3452 :
 SAVE TO FILE  ?

     MENU
1 - LOAD ANTENNA IMPEDANCE FILE
2 - DETERMINE NETWORK CANDIDATES
3 - OPTIMIZE SELECTED NETWORK
4 - ADJUST COMPONENT VALUE MANUALLY
5 - LIST NETWORK CANDIDATES
6 - DIGITIZE IMPEDANCE PLOT FROM TABLET
7 - EXIT
SELECTION (1-7) ? 7
```

5.4 DETERMINE NETWORK CANDIDATES HAVING TWO COMPONENTS

This section presents how to find network candidates having two components. The procedure of finding network candidates having two components is similar to that of finding network candidates having one component as discussed in section 5.2. The results are shown in the following:

```
HP PLOTTER TYPE: 2 PENS OR 6 PENS -- (HP2 / HP6) ? HP6
        MENU
1 - LOAD ANTENNA IMPEDANCE FILE
2 - DETERMINE NETWORK CANDIDATES
3 - OPTIMIZE SELECTED NETWORK
4 - ADJUST COMPONENT VALUE MANUALLY
5 - LIST NETWORK CANDIDATES
6 - DIGITIZE IMPEDANCE PLOT FROM TABLET
7 - EXIT
SELECTION (1-7) ? 2
  IMPEDANCE INPUT
IMPEDANCE IS NORMALIZED (Y/N) ? Y
IMPEDANCE FILE                ? SAMP1.IMP
  IMPEDANCE DATA
```

NUMBER	FREQ (MHZ)	RESISTANCE	REACTANCE	VSWR
1	2	2.07	-1.27	2.998804
2	2.2	.54	- .93	3.725066
3	2.4	.62	- .67	2.567443
4	2.6	.83	- .47	1.719348
5	2.8	.96	- .45	1.579487
6	3	1.21	- .2	1.300669
7	3.2	1.51	.01	1.510118
8	3.4	1.86	- .39	1.972416
9	3.6	1.33	- .9	2.245584
10	3.8	.93	- .54	1.746119
11	4	.66	- .18	1.598756
12	4.2	.65	.24	1.682845
13	4.4	.77	.49	1.835797
14	4.6	.78	.79	2.454817
15	4.8	.71	.75	2.512731
16	5	.89	.89	2.504279
17	5.2	1.21	.99	2.435924
18	5.4	.88	1.06	2.954742
19	5.6	.95	1.3	3.495497
20	5.8	1.12	1.01	2.528108
21	6	1.33	1.92	4.637999

```
DISPLAY SMITH CHART (Y/N)? N

OUTPUT TO HP PLOTTER  (Y/N) ? N
      NETWORK
NUMBER OF NETWORK COMPONENTS (1-6) ? 2
UPPER LIMIT ON ITERATIONS =  60   ?
LOWER LIMIT ON ITERATIONS =  30   ?
EVALUATED NETWORK  5
EVALUATED NETWORK  6
EVALUATED NETWORK  7
```

```
EVALUATED NETWORK  8
EVALUATED NETWORK  9
EVALUATED NETWORK  10
EVALUATED NETWORK  11
EVALUATED NETWORK  12
EVALUATED NETWORK  13
EVALUATED NETWORK  14
  NETWORK RESULTS

NET =     7     10     6      8     14     13
 FREQ   VSWR   VSWR   VSWR   VSWR   VSWR   VSWR
 2.00   2.5    3.8    2.4    3.1    3.0    3.0
 2.20   3.5    2.2    2.0    4.1    3.8    2.6
 2.40   2.6    1.5    2.0    2.8    2.6    1.8
 2.60   1.8    1.1    1.6    1.9    1.8    1.2
 2.80   1.7    1.2    1.4    1.8    1.6    1.2
 3.00   1.2    1.3    1.3    1.4    1.3    1.3
 3.20   1.0    1.6    1.4    1.6    1.5    1.7
 3.40   1.4    1.9    1.4    2.1    2.0    2.0
 3.60   2.1    2.1    1.6    2.5    2.3    2.0
 3.80   2.3    1.7    1.5    2.0    1.8    1.4
 4.00   2.8    1.6    1.9    1.8    1.6    1.4
 4.20   2.6    1.6    2.2    1.5    1.6    1.9
 4.40   2.2    1.6    2.2    1.5    1.8    2.2
 4.60   2.2    2.0    2.7    2.0    2.4    2.9
 4.80   2.3    2.0    2.8    2.1    2.4    3.0
 5.00   1.8    1.9    2.6    2.1    2.4    3.0
 5.20   1.3    2.0    2.4    2.1    2.4    2.8
 5.40   1.7    2.2    3.0    2.5    2.8    3.4
 5.60   1.4    2.7    3.4    3.0    3.4    4.0
 5.80   1.3    2.0    2.5    2.1    2.4    2.9
 6.00   1.7    4.2    4.4    4.2    4.5    5.1

(NETWORKS RANKED FROM BEST TO WORST)

  7 T-SS-C-L  =487.8821 : 1.70243 :
  10 T-SS-LCP-SS  =3.797296 : 458.5816 :
  6 T-SS-L-C  =3.747538 : 1486.14 :
? 8 T-SS-C-C  =130.6055 : 2373013 :
? 14 T-C-C-SS  =3.314653E+07 : 23.55746 :
? 13 T-C-L-SS  =235894.6 : 9.263759 :
 SAVE TO FILE  ? NETWORK2.LIB

        MENU
1 - LOAD ANTENNA IMPEDANCE FILE
2 - DETERMINE NETWORK CANDIDATES
3 - OPTIMIZE SELECTED NETWORK
4 - ADJUST COMPONENT VALUE MANUALLY
5 - LIST NETWORK CANDIDATES
6 - DIGITIZE IMPEDANCE PLOT FROM TABLET
7 - EXIT
SELECTION (1-7) ? 7
```

Network candidates, ranked from best to worst, are network numbers 7, 10, 6, 8, 14, and 13. The results are saved in a library file called NETWORK2.LIB for future use.

5.5 OPTIMIZE THE SELECTED NETWORKS HAVING TWO COMPONENTS

Network number 7 is ranked as best among the network candidates having two components saved in the file NETWORK2.LIB. Therefore, network number 7 is chosen to be optimized. The optimization procedure is similar to that discussed in section 5.3. The around-the-average weighting function is used. The results, as shown in the following, indicate that network number 7 is not acceptable because it does not provide a maximum VSWR of 3:1 over the operating band from 2 to 6 MHz.

```
HP PLOTTER TYPE: 2 PENS OR 6 PENS -- (HP2 / HP6) ? HP6
        MENU
1 - LOAD ANTENNA IMPEDANCE FILE
2 - DETERMINE NETWORK CANDIDATES
3 - OPTIMIZE SELECTED NETWORK
4 - ADJUST COMPONENT VALUE MANUALLY
5 - LIST NETWORK CANDIDATES
6 - DIGITIZE IMPEDANCE PLOT FROM TABLET
7 - EXIT
SELECTION (1-7) ? 1
  IMPEDANCE INPUT
IMPEDANCE IS NORMALIZED (Y/N) ? Y
IMPEDANCE FILE              ? SAMP1.IMP
  IMPEDANCE DATA
NUMBER        FREQ (MHZ)    RESISTANCE    REACTANCE     VSWR

1             2             2.07          -1.27         2.998804
2             2.2            .54          - .93         3.725066
3             2.4            .62          - .67         2.567443
4             2.6            .83          - .47         1.719348
5             2.8            .96          - .45         1.579487
6             3             1.21          - .2          1.300669
7             3.2           1.51            .01         1.510118
8             3.4           1.86          - .39         1.972416
9             3.6           1.33          - .9          2.245584
10            3.8            .93          - .54         1.746119
11            4              .66          - .18         1.598756
12            4.2            .65            .24         1.682845
13            4.4            .77            .49         1.835797
14            4.6            .78            .79         2.454817
15            4.8            .71            .75         2.512731
16            5              .89            .89         2.504279
17            5.2           1.21            .99         2.435924
18            5.4            .88          1.06          2.954742
19            5.6            .95          1.3           3.495497
20            5.8           1.12          1.01          2.528108
21            6             1.33          1.92          4.637999
```

```
DISPLAY SMITH CHART (Y/N)? N

OUTPUT TO HP PLOTTER  (Y/N) ? N
        MENU
1 - LOAD ANTENNA IMPEDANCE FILE
2 - DETERMINE NETWORK CANDIDATES
3 - OPTIMIZE SELECTED NETWORK
4 - ADJUST COMPONENT VALUE MANUALLY
5 - LIST NETWORK CANDIDATES
6 - DIGITIZE IMPEDANCE PLOT FROM TABLET
7 - EXIT
SELECTION (1-7) ? 5
    NETWORK LIST
NETWORK NUMBER [ L (OAD), A (LL), #, Q (UIT) ] ? L
FILE NAME =  ? NETWORK2.LIB
  7 T-SS-C-L  =487.8821 : 1.70243 :
  10 T-SS-LCP-SS  =3.797296 : 458.5816 :
  6 T-SS-L-C  =3.747538 : 1486.14 :
? 8 T-SS-C-C  =130.6055 : 2373013 :
? 14 T-C-C-SS  =3.314653E+07 : 23.55746 :
? 13 T-C-L-SS  =235894.6 : 9.263759 :

NETWORK NUMBER [ L (OAD), A (LL), #, Q (UIT) ] ? Q
        MENU
1 - LOAD ANTENNA IMPEDANCE FILE
2 - DETERMINE NETWORK CANDIDATES
3 - OPTIMIZE SELECTED NETWORK
4 - ADJUST COMPONENT VALUE MANUALLY
5 - LIST NETWORK CANDIDATES
6 - DIGITIZE IMPEDANCE PLOT FROM TABLET
7 - EXIT
SELECTION (1-7) ? 3
    OPTIMIZATION
NETWORK TO BE OPTIMIZED ? 7
T NETWORK CONFIGURATION:
COMPONENT NO.  1  SHORT CIRCUIT SERIES
COMPONENT NO.  2  CAPACITOR
 487.8821  PICOFARADS
COMPONENT NO.  3  INDUCTOR
 1.70243  MICROHENRIES
DISPLAY SMITH CHART (Y/N)? N

OUTPUT TO HP PLOTTER  (Y/N) ? N
UPPER LIMIT ON ITERATIONS =  200   ?
LOWER LIMIT ON ITERATIONS =  100   ?
1 - EXPONENTIAL WEIGHTING FUNCTION
2 - AROUND THE AVERAGE WEIGHTING FUNCTION
3 - USER INPUT WEIGHTS ON SELECTED FREQUENCIES
4 - WEIGHT IS 1 ON ALL FREQUENCY POINTS
SELECTION (1-4) ? 2
SECOND MULTIPLIER FOR AVERAGE WEIGHTING  =  1  ?
FIRST MULTIPLIER FOR AVERAGE WEIGHTING =  2  ? 5
```

FREQ (MHZ)	RESISTANCE	REACTANCE	VSWR	OLD-VSWR	WEIGHT
2	.9717299	-1.054946	2.8	2.5	3.7
2.2	.3250062	- .4430693	3.7	3.5	8.8
2.4	.4059365	- .2621987	2.7	2.6	4.2
2.6	.5735163	- .1630094	1.8	1.8	1.0
2.8	.6370243	- .1691475	1.6	1.7	1.0
3	.8552131	- .1323038	1.2	1.2	1.0
3.2	1.059795	- .217597	1.2	1.0	1.0
3.4	.8705592	- .4629184	1.7	1.4	1.0
3.6	.531251	- .3324547	2.2	2.1	1.6
3.8	.4975178	-4.731125E-02	2.0	2.3	2.6
4	.4942914	.2656525	2.2	2.8	5.1
4.2	.7365093	.5816853	2.1	2.6	4.3
4.4	1.081656	.6374084	1.8	2.2	2.2
4.6	1.579336	.7155927	2.0	2.2	2.0
4.8	1.494119	.8200412	2.1	2.3	2.8
5	1.702942	.377119	1.8	1.8	1.0
5.2	1.468138	- .1311723	1.5	1.3	1.0
5.4	1.88159	7.888954E-02	1.9	1.7	1.0
5.6	1.807615	- .4624159	2.0	1.4	1.0
5.8	1.358882	-9.787453E-02	1.4	1.3	1.0
6	.8825849	- .7983334	2.3	1.7	1.0

DISPLAY SMITH CHART (Y/N)? N

OUTPUT TO HP PLOTTER (Y/N) ? N
NETWORK RESULTS

NET = 7

FREQ	VSWR
2.00	2.8
2.20	3.7
2.40	2.7
2.60	1.8
2.80	1.6
3.00	1.2
3.20	1.2
3.40	1.7
3.60	2.2
3.80	2.0
4.00	2.2
4.20	2.1
4.40	1.8
4.60	2.0
4.80	2.1
5.00	1.8
5.20	1.5
5.40	1.9
5.60	2.0
5.80	1.4
6.00	2.3

(NETWORKS RANKED FROM BEST TO WORST)

7 T-SS-C-L =433.7313 : 1.176743 :
SAVE TO FILE NETWORK2.LIB ?

```
        MENU
1 - LOAD ANTENNA IMPEDANCE FILE
2 - DETERMINE NETWORK CANDIDATES
3 - OPTIMIZE SELECTED NETWORK
4 - ADJUST COMPONENT VALUE MANUALLY
5 - LIST NETWORK CANDIDATES
6 - DIGITIZE IMPEDANCE PLOT FROM TABLET
7 - EXIT
SELECTION (1-7) ? 3
    OPTIMIZATION
NETWORK TO BE OPTIMIZED ? 7
T NETWORK CONFIGURATION:
COMPONENT NO.  1  SHORT CIRCUIT SERIES
COMPONENT NO.  2  CAPACITOR
 433.7313  PICOFARADS
COMPONENT NO.  3  INDUCTOR
 1.176743  MICROHENRIES
DISPLAY SMITH CHART (Y/N)? N

OUTPUT TO HP PLOTTER  (Y/N) ? N
UPPER LIMIT ON ITERATIONS =  200   ?
LOWER LIMIT ON ITERATIONS =  100   ?
1 - EXPONENTIAL WEIGHTING FUNCTION
2 - AROUND THE AVERAGE WEIGHTING FUNCTION
3 - USER INPUT WEIGHTS ON SELECTED FREQUENCIES
4 - WEIGHT IS 1 ON ALL FREQUENCY POINTS
SELECTION (1-4) ? 2
SECOND MULTIPLIER FOR AVERAGE WEIGHTING  =  1  ?
FIRST MULTIPLIER FOR AVERAGE WEIGHTING =  2  ? 15
```

FREQ (MHZ)	RESISTANCE	REACTANCE	VSWR	OLD-VSWR	WEIGHT
2	1.048295	- .9109449	2.4	2.8	12.7
2.2	.3408185	- .2740766	3.2	3.7	27.0
2.4	.4231194	-6.856636E-02	2.4	2.7	10.9
2.6	.5966626	.0560487	1.7	1.8	1.0
2.8	.6665623	6.844242E-02	1.5	1.6	1.0
3	.8966686	.1372608	1.2	1.2	1.0
3.2	1.125463	8.295898E-02	1.2	1.2	1.0
3.4	.9541361	- .1835604	1.2	1.7	1.0
3.6	.5800065	-5.434075E-02	1.7	2.2	3.3
3.8	.5307994	.2647092	2.1	2.0	2.6
4	.5123189	.6085908	2.8	2.2	5.1
4.2	.7385369	.9647896	3.0	2.1	4.3
4.4	1.078673	1.076955	2.7	1.8	2.2
4.6	1.556373	1.25729	2.9	2.0	2.0
4.8	1.458044	1.365204	3.1	2.1	3.1
5	1.766051	1.000667	2.5	1.8	1.0
5.2	1.658421	.4295549	1.8	1.5	1.0
5.4	2.056913	.7969131	2.4	1.9	1.0
5.6	2.180936	.2032934	2.2	2.0	1.0
5.8	1.573266	.4944133	1.8	1.4	1.0
6	1.186638	- .4707363	1.6	2.3	5.5

```
DISPLAY SMITH CHART (Y/N)? N

OUTPUT TO HP PLOTTER  (Y/N) ? N
  NETWORK RESULTS
```

```
NET =     7
 FREQ   VSWR
 2.00    2.4
 2.20    3.2
 2.40    2.4
 2.60    1.7
 2.80    1.5
 3.00    1.2
 3.20    1.2
 3.40    1.2
 3.60    1.7
 3.80    2.1
 4.00    2.8
 4.20    3.0
 4.40    2.7
 4.60    2.9
 4.80    3.1
 5.00    2.5
 5.20    1.8
 5.40    2.4
 5.60    2.2
 5.80    1.8
 6.00    1.6

(NETWORKS RANKED FROM BEST TO WORST)

  7 T-SS-C-L  =389.437 : 1.842411 :
 SAVE TO FILE  ?

         MENU
1 - LOAD ANTENNA IMPEDANCE FILE
2 - DETERMINE NETWORK CANDIDATES
3 - OPTIMIZE SELECTED NETWORK
4 - ADJUST COMPONENT VALUE MANUALLY
5 - LIST NETWORK CANDIDATES
6 - DIGITIZE IMPEDANCE PLOT FROM TABLET
7 - EXIT
SELECTION (1-7) ? 7
```

We can try to optimize network number 7 by using other weighting functions such as the "exponential weighting function" and "user input weights on selected frequencies." Unfortunately, the results are not satisfactory either.

Next, we will select "list of network candidates" from the menu to find out which network candidate is ranked the second best. Network number 10 is the second best and is chosen to be optimized. However, the results indicate again that network number 10 is not acceptable. The results are given below:

```
HP PLOTTER TYPE: 2 PENS OR 6 PENS -- (HP2 / HP6) ? HP6
        MENU
1 - LOAD ANTENNA IMPEDANCE FILE
2 - DETERMINE NETWORK CANDIDATES
3 - OPTIMIZE SELECTED NETWORK
4 - ADJUST COMPONENT VALUE MANUALLY
5 - LIST NETWORK CANDIDATES
6 - DIGITIZE IMPEDANCE PLOT FROM TABLET
7 - EXIT
SELECTION (1-7) ? 1
  IMPEDANCE INPUT
IMPEDANCE IS NORMALIZED (Y/N) ? Y
IMPEDANCE FILE                ? SAMP1.IMP
  IMPEDANCE DATA

NUMBER        FREQ (MHZ)    RESISTANCE    REACTANCE     VSWR

1             2             2.07          -1.27         2.998804
2             2.2            .54          - .93         3.725066
3             2.4            .62          - .67         2.567443
4             2.6            .83          - .47         1.719348
5             2.8            .96          - .45         1.579487
6             3             1.21          - .2          1.300669
7             3.2           1.51            .01         1.510118
8             3.4           1.86          - .39         1.972416
9             3.6           1.33          - .9          2.245584
10            3.8            .93          - .54         1.746119
11            4              .66          - .18         1.598756
12            4.2            .65            .24         1.682845
13            4.4            .77            .49         1.835797
14            4.6            .78            .79         2.454817
15            4.8            .71            .75         2.512731
16            5              .89            .89         2.504279
17            5.2           1.21            .99         2.435924
18            5.4            .88           1.06         2.954742
19            5.6            .95           1.3          3.495497
20            5.8           1.12           1.01         2.528108
21            6             1.33           1.92         4.637999

DISPLAY SMITH CHART (Y/N)? N

OUTPUT TO HP PLOTTER  (Y/N) ? N
        MENU
1 - LOAD ANTENNA IMPEDANCE FILE
2 - DETERMINE NETWORK CANDIDATES
3 - OPTIMIZE SELECTED NETWORK
4 - ADJUST COMPONENT VALUE MANUALLY
5 - LIST NETWORK CANDIDATES
6 - DIGITIZE IMPEDANCE PLOT FROM TABLET
7 - EXIT
SELECTION (1-7) ? 5
    NETWORK LIST
NETWORK NUMBER [ L (OAD), A (LL), #, Q (UIT) ] ? L
FILE NAME =  ? NETWORK2.LIB
  7 T-SS-C-L  =487.8821 : 1.70243 :
  10 T-SS-LCP-SS  =3.797296 : 458.5816 :
  6 T-SS-L-C  =3.747538 : 1486.14 :
```

```
? 8 T-SS-C-C  =130.6055 : 2373013 :
? 14 T-C-C-SS  =3.314653E+07 : 23.55746 :
? 13 T-C-L-SS  =235894.6 : 9.263759 :

NETWORK NUMBER [ L (OAD), A (LL), #, Q (UIT) ] ? Q
        MENU
1 - LOAD ANTENNA IMPEDANCE FILE
2 - DETERMINE NETWORK CANDIDATES
3 - OPTIMIZE SELECTED NETWORK
4 - ADJUST COMPONENT VALUE MANUALLY
5 - LIST NETWORK CANDIDATES
6 - DIGITIZE IMPEDANCE PLOT FROM TABLET
7 - EXIT
SELECTION (1-7) ? 3
    OPTIMIZATION
NETWORK TO BE OPTIMIZED ? 10
T NETWORK CONFIGURATION:
COMPONENT NO.  1  SHORT CIRCUIT SERIES
COMPONENT NO.  2  PARALLEL INDUCTOR, CAPACITOR
 3.797296  MICROHENRIES,  458.5816  PICOFARADS
COMPONENT NO.  3  SHORT CIRCUIT SERIES
DISPLAY SMITH CHART (Y/N)? N

OUTPUT TO HP PLOTTER  (Y/N) ? N
UPPER LIMIT ON ITERATIONS =  200   ?
LOWER LIMIT ON ITERATIONS =  100   ?
1 - EXPONENTIAL WEIGHTING FUNCTION
2 - AROUND THE AVERAGE WEIGHTING FUNCTION
3 - USER INPUT WEIGHTS ON SELECTED FREQUENCIES
4 - WEIGHT IS 1 ON ALL FREQUENCY POINTS
SELECTION (1-4) ? 2
SECOND MULTIPLIER FOR AVERAGE WEIGHTING  =  1  ?
FIRST MULTIPLIER FOR AVERAGE WEIGHTING =  2  ? 5
```

FREQ (MHZ)	RESISTANCE	REACTANCE	VSWR	OLD-VSWR	WEIGHT
2	2.432508	1.006755	2.9	3.8	9.8
2.2	.9634321	-1.065434	2.8	2.2	2.0
2.4	.8355616	- .6518118	2.1	1.5	1.0
2.6	.9551598	- .3669645	1.5	1.1	1.0
2.8	1.052477	- .3530963	1.4	1.2	1.0
3	1.234423	- .1032452	1.3	1.3	1.0
3.2	1.507858	5.770988E-02	1.5	1.6	1.0
3.4	1.827209	- .4575301	2.0	1.9	1.0
3.6	1.189101	- .9443159	2.4	2.1	1.6
3.8	.8324208	- .5850052	1.9	1.7	1.0
4	.6245667	- .2297628	1.7	1.6	1.0
4.2	.696917	.1704708	1.5	1.6	1.0
4.4	.9210445	.3848113	1.5	1.6	1.0
4.6	1.118286	.7186597	2.0	2.0	1.0
4.8	1.048941	.6895639	1.9	2.0	1.0
5	1.454507	.6880643	2.0	1.9	1.0
5.2	1.969506	.3153542	2.0	2.0	1.0
5.4	1.808089	.794061	2.3	2.2	2.0
5.6	2.472261	.7966158	2.8	2.7	4.6
5.8	2.02189	.1342453	2.0	2.0	1.0
6	3.639088	-1.297534	4.1	4.2	12.0

```
DISPLAY SMITH CHART (Y/N)? N
```

```
OUTPUT TO HP PLOTTER  (Y/N) ? N
  NETWORK RESULTS

NET =   10
 FREQ  VSWR
 2.00   2.9
 2.20   2.8
 2.40   2.1
 2.60   1.5
 2.80   1.4
 3.00   1.3
 3.20   1.5
 3.40   2.0
 3.60   2.4
 3.80   1.9
 4.00   1.7
 4.20   1.5
 4.40   1.5
 4.60   2.0
 4.80   1.9
 5.00   2.0
 5.20   2.0
 5.40   2.3
 5.60   2.8
 5.80   2.0
 6.00   4.1

(NETWORKS RANKED FROM BEST TO WORST)

  10 T-SS-LCP-SS  =6.97742 : 333.675 :
 SAVE TO FILE NETWORK2.LIB ?

         MENU
1 - LOAD ANTENNA IMPEDANCE FILE
2 - DETERMINE NETWORK CANDIDATES
3 - OPTIMIZE SELECTED NETWORK
4 - ADJUST COMPONENT VALUE MANUALLY
5 - LIST NETWORK CANDIDATES
6 - DIGITIZE IMPEDANCE PLOT FROM TABLET
7 - EXIT
SELECTION (1-7) ? 3
    OPTIMIZATION
NETWORK TO BE OPTIMIZED ? 10
T NETWORK CONFIGURATION:
COMPONENT NO.  1  SHORT CIRCUIT SERIES
COMPONENT NO.  2  PARALLEL INDUCTOR, CAPACITOR
6.97742  MICROHENRIES,  333.675  PICOFARADS
COMPONENT NO.  3  SHORT CIRCUIT SERIES
DISPLAY SMITH CHART (Y/N)? N

OUTPUT TO HP PLOTTER  (Y/N) ? N
UPPER LIMIT ON ITERATIONS =  200   ?
LOWER LIMIT ON ITERATIONS =  100   ?
```

1 - EXPONENTIAL WEIGHTING FUNCTION
2 - AROUND THE AVERAGE WEIGHTING FUNCTION
3 - USER INPUT WEIGHTS ON SELECTED FREQUENCIES
4 - WEIGHT IS 1 ON ALL FREQUENCY POINTS
SELECTION (1-4) ? 2
SECOND MULTIPLIER FOR AVERAGE WEIGHTING = 1 ?
FIRST MULTIPLIER FOR AVERAGE WEIGHTING = 2 ? 15

FREQ (MHZ)	RESISTANCE	REACTANCE	VSWR	OLD-VSWR	WEIGHT
2	1.534252	1.420362	3.2	2.9	13.6
2.2	1.354687	-1.032526	2.5	2.8	12.3
2.4	1.000273	- .58639	1.8	2.1	1.0
2.6	1.035784	- .2500404	1.3	1.5	1.0
2.8	1.127094	- .2222971	1.3	1.4	1.0
3	1.239988	6.170021E-02	1.2	1.3	1.0
3.2	1.459665	.2712354	1.5	1.5	1.0
3.4	1.930191	- .1495244	1.9	2.0	1.0
3.6	1.379723	- .8784521	2.2	2.4	5.2
3.8	.9057207	- .5531523	1.8	1.9	1.0
4	.6431939	- .2058751	1.7	1.7	1.0
4.2	.6813666	.1975029	1.6	1.5	1.0
4.4	.8806752	.4208819	1.6	1.5	1.0
4.6	1.03868	.7499276	2.1	2.0	1.0
4.8	.9844061	.7139833	2.0	1.9	1.0
5	1.372281	.7480007	2.0	2.0	1.0
5.2	1.916168	.4460493	2.1	2.0	1.0
5.4	1.715015	.8704589	2.3	2.3	3.9
5.6	2.356373	.9369763	2.8	2.8	11.5
5.8	2.004473	.2297366	2.0	2.0	1.0
6	3.81436	-1.046962	4.1	4.1	31.9

DISPLAY SMITH CHART (Y/N)? N
OUTPUT TO HP PLOTTER (Y/N) ? N
NETWORK RESULTS
NET = 10

FREQ	VSWR
2.00	3.2
2.20	2.5
2.40	1.8
2.60	1.3
2.80	1.3
3.00	1.2
3.20	1.5
3.40	1.9
3.60	2.2
3.80	1.8
4.00	1.7
4.20	1.6
4.40	1.6
4.60	2.1
4.80	2.0
5.00	2.0
5.20	2.1
5.40	2.3
5.60	2.8
5.80	2.0
6.00	4.1

```
(NETWORKS RANKED FROM BEST TO WORST)
  10 T-SS-LCP-SS  =5.202042 : 357.4753 :
 SAVE TO FILE  ?
        MENU
1 - LOAD ANTENNA IMPEDANCE FILE
2 - DETERMINE NETWORK CANDIDATES
3 - OPTIMIZE SELECTED NETWORK
4 - ADJUST COMPONENT VALUE MANUALLY
5 - LIST NETWORK CANDIDATES
6 - DIGITIZE IMPEDANCE PLOT FROM TABLET
7 - EXIT
SELECTION (1-7) ? 3
    OPTIMIZATION
NETWORK TO BE OPTIMIZED ? 10
T NETWORK CONFIGURATION:
COMPONENT NO.  1  SHORT CIRCUIT SERIES
COMPONENT NO.  2  PARALLEL INDUCTOR, CAPACITOR
 5.202042  MICROHENRIES,  357.4753  PICOFARADS
COMPONENT NO.  3  SHORT CIRCUIT SERIES
DISPLAY SMITH CHART (Y/N)? N

OUTPUT TO HP PLOTTER  (Y/N) ? N
UPPER LIMIT ON ITERATIONS =  200   ?
LOWER LIMIT ON ITERATIONS =  100   ?
1 - EXPONENTIAL WEIGHTING FUNCTION
2 - AROUND THE AVERAGE WEIGHTING FUNCTION
3 - USER INPUT WEIGHTS ON SELECTED FREQUENCIES
4 - WEIGHT IS 1 ON ALL FREQUENCY POINTS
SELECTION (1-4) ? 2
SECOND MULTIPLIER FOR AVERAGE WEIGHTING  =  1  ?
FIRST MULTIPLIER FOR AVERAGE WEIGHTING =  2  ? 30
```

FREQ (MHZ)	RESISTANCE	REACTANCE	VSWR	OLD-VSWR	WEIGHT
2	2.333414	1.097038	2.9	3.2	35.2
2.2	1.003526	-1.068716	2.8	2.5	13.9
2.4	.8560569	- .646324	2.0	1.8	1.0
2.6	.9678792	- .3523428	1.4	1.3	1.0
2.8	1.065765	- .334797	1.4	1.3	1.0
3	1.238444	-7.558729E-02	1.3	1.2	1.0
3.2	1.503561	9.890186E-02	1.5	1.5	1.0
3.4	1.856104	- .3987645	2.0	1.9	1.0
3.6	1.231068	- .9335632	2.3	2.2	6.0
3.8	.8506937	- .5780995	1.9	1.8	1.0
4	.6299404	- .2232937	1.7	1.7	1.0
4.2	.6922582	.17914	1.5	1.6	1.0
4.4	.9070957	.398108	1.5	1.6	1.0
4.6	1.086578	.7323118	2.0	2.1	1.3
4.8	1.019911	.701389	2.0	2.0	1.0
5	1.41301	.7201119	2.0	2.0	1.0
5.2	1.940496	.3927808	2.0	2.1	1.3
5.4	1.745809	.8470793	2.3	2.3	8.8
5.6	2.382046	.90903	2.8	2.8	23.5
5.8	2.005877	.2236075	2.0	2.0	1.0
6	3.835087	-1.011237	4.1	4.1	63.2

```
DISPLAY SMITH CHART (Y/N)? N

OUTPUT TO HP PLOTTER  (Y/N) ? N
  NETWORK RESULTS

NET =    10
 FREQ   VSWR
 2.00    2.9
 2.20    2.8
 2.40    2.0
 2.60    1.4
 2.80    1.4
 3.00    1.3
 3.20    1.5
 3.40    2.0
 3.60    2.3
 3.80    1.9
 4.00    1.7
 4.20    1.5
 4.40    1.5
 4.60    2.0
 4.80    2.0
 5.00    2.0
 5.20    2.0
 5.40    2.3
 5.60    2.8
 5.80    2.0
 6.00    4.1

(NETWORKS RANKED FROM BEST TO WORST)

  10 T-SS-LCP-SS   =6.813416 : 324.09 :
 SAVE TO FILE  ?

    MENU
1 - LOAD ANTENNA IMPEDANCE FILE
2 - DETERMINE NETWORK CANDIDATES
3 - OPTIMIZE SELECTED NETWORK
4 - ADJUST COMPONENT VALUE MANUALLY
5 - LIST NETWORK CANDIDATES
6 - DIGITIZE IMPEDANCE PLOT FROM TABLET
7 - EXIT
SELECTION (1-7) ? 7
```

We can either continue the same process and try to optimize the other network candidates having two components or increase the number of network components. We decide to increase the number of network components from two to three. The next section will discuss how to determine network candidates having three components.

5.6 DETERMINE NETWORK CANDIDATES HAVING THREE COMPONENTS

The procedure of finding network candidates having three components is similar to that of finding network candidates having one component as discussed in section 5.2. The results are shown in the following:

```
HP PLOTTER TYPE: 2 PENS OR 6 PENS -- (HP2 / HP6) ? HP6
         MENU
1 - LOAD ANTENNA IMPEDANCE FILE
2 - DETERMINE NETWORK CANDIDATES
3 - OPTIMIZE SELECTED NETWORK
4 - ADJUST COMPONENT VALUE MANUALLY
5 - LIST NETWORK CANDIDATES
6 - DIGITIZE IMPEDANCE PLOT FROM TABLET
7 - EXIT
SELECTION (1-7) ? 2
  IMPEDANCE INPUT
IMPEDANCE IS NORMALIZED (Y/N) ? Y
IMPEDANCE FILE                ? SAMP1.IMP
  IMPEDANCE DATA
```

NUMBER	FREQ (MHZ)	RESISTANCE	REACTANCE	VSWR
1	2	2.07	-1.27	2.998804
2	2.2	.54	- .93	3.725066
3	2.4	.62	- .67	2.567443
4	2.6	.83	- .47	1.719348
5	2.8	.96	- .45	1.579487
6	3	1.21	- .2	1.300669
7	3.2	1.51	.01	1.510118
8	3.4	1.86	- .39	1.972416
9	3.6	1.33	- .9	2.245584
10	3.8	.93	- .54	1.746119
11	4	.66	- .18	1.598756
12	4.2	.65	.24	1.682845
13	4.4	.77	.49	1.835797
14	4.6	.78	.79	2.454817
15	4.8	.71	.75	2.512731
16	5	.89	.89	2.504279
17	5.2	1.21	.99	2.435924
18	5.4	.88	1.06	2.954742
19	5.6	.95	1.3	3.495497
20	5.8	1.12	1.01	2.528108
21	6	1.33	1.92	4.637999

DISPLAY SMITH CHART (Y/N)? N

OUTPUT TO HP PLOTTER (Y/N) ? N
NETWORK
NUMBER OF NETWORK COMPONENTS (1-6) ? 3
UPPER LIMIT ON ITERATIONS = 60 ?
LOWER LIMIT ON ITERATIONS = 30 ?
EVALUATED NETWORK 15
EVALUATED NETWORK 16
EVALUATED NETWORK 17
EVALUATED NETWORK 18
EVALUATED NETWORK 19
EVALUATED NETWORK 20
EVALUATED NETWORK 21
EVALUATED NETWORK 22
EVALUATED NETWORK 23
EVALUATED NETWORK 24
EVALUATED NETWORK 25
EVALUATED NETWORK 26
EVALUATED NETWORK 27
EVALUATED NETWORK 28
EVALUATED NETWORK 29
EVALUATED NETWORK 30
EVALUATED NETWORK 31
EVALUATED NETWORK 32
EVALUATED NETWORK 33
EVALUATED NETWORK 34
EVALUATED NETWORK 35
EVALUATED NETWORK 36
EVALUATED NETWORK 37
EVALUATED NETWORK 38
NETWORK RESULTS

NET =	17	35	21	33	36	28	18	25	38	16
FREQ	VSWR	VSWR	VSWR	VSWR	VSWR	VSWR	VSWR	VSWR	VSWR	VSWR
2.00	2.8	2.0	2.3	1.8	3.6	4.1	4.8	4.6	3.3	6.2
2.20	2.2	2.7	3.2	2.7	4.5	2.4	1.2	1.6	4.5	8.3
2.40	1.7	2.3	2.5	2.6	3.0	1.6	1.6	1.5	3.1	5.0
2.60	1.3	1.8	1.8	2.0	2.0	1.2	1.6	1.5	2.1	3.0
2.80	1.2	1.6	1.6	1.7	1.8	1.2	1.4	1.4	1.9	2.5
3.00	1.2	1.3	1.3	1.3	1.5	1.3	1.3	1.3	1.6	1.8
3.20	1.4	1.2	1.1	1.2	1.7	1.6	1.3	1.3	1.6	1.7
3.40	1.3	1.2	1.2	1.3	2.1	2.0	1.4	1.3	2.2	2.1
3.60	1.6	2.0	1.9	1.8	2.4	2.1	1.8	1.7	2.8	2.6
3.80	1.9	2.4	2.3	1.8	1.8	1.7	1.9	1.8	2.3	2.2
4.00	2.6	3.0	3.0	2.1	1.8	1.6	2.1	2.2	1.9	2.3
4.20	2.8	2.8	2.9	2.1	1.9	1.6	1.9	2.2	1.4	2.1
4.40	2.4	2.3	2.5	2.0	1.9	1.6	1.6	2.0	1.4	1.9
4.60	2.5	2.2	2.5	2.4	2.3	2.0	1.9	2.4	1.8	2.1
4.80	2.6	2.4	2.6	2.5	2.4	2.0	1.9	2.4	1.9	2.2
5.00	2.0	1.8	2.0	2.4	2.0	1.9	1.7	2.2	1.9	1.8
5.20	1.4	1.3	1.4	2.2	1.5	2.0	1.7	2.0	2.0	1.3
5.40	1.7	1.6	1.8	2.7	1.9	2.2	2.0	2.5	2.3	1.7
5.60	1.5	1.4	1.5	3.1	1.7	2.7	2.4	2.8	2.8	1.5
5.80	1.3	1.2	1.3	2.3	1.4	2.0	1.8	2.0	2.0	1.4
6.00	1.7	1.8	1.7	4.1	1.5	4.1	3.7	3.6	4.0	1.5

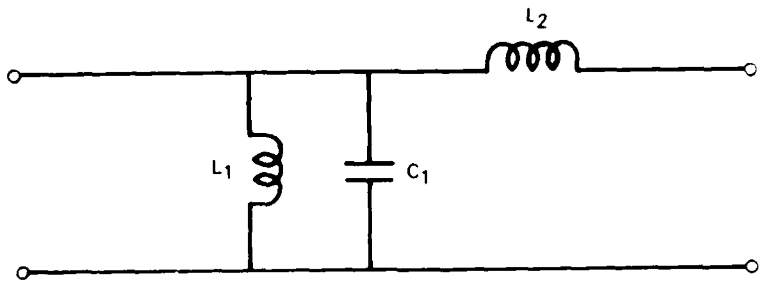
```
NET =    20    30
 FREQ   VSWR  VSWR
 2.00    4.2   7.7
 2.20   11.3  16.7
 2.40    8.1  11.3
 2.60    5.2   7.1
 2.80    4.2   5.8
 3.00    2.9   4.0
 3.20    2.2   3.0
 3.40    2.6   3.7
 3.60    3.8   5.3
 3.80    3.7   5.0
 4.00    3.5   4.5
 4.20    2.4   2.9
 4.40    1.7   1.9
 4.60    1.5   1.4
 4.80    1.6   1.5
 5.00    1.4   1.1
 5.20    1.4   1.3
 5.40    1.7   1.2
 5.60    2.0   1.6
 5.80    1.5   1.3
 6.00    3.0   2.7

 (NETWORKS RANKED FROM BEST TO WORST)

   17 T-SS-LCP-L  =7.400042 : 591.4796 : 1.677851 :
   35 PI-C-L-L  =500.5644 : 1.374559 : 7.746106 :
 ? 21 T-L-C-L  =.2423867 : 473.3028 : 1.915353 :
 ? 33 PI-L-C-L  =4.175326 : 1068.759 : 14.4645 :
   36 PI-C-L-C  =661.1556 : 2.050835 : 619.4227 :
 ? 28 T-C-LCP-SS  =25414.66 : 3.59574 : 452.4102 :
   18 T-SS-LCP-C  =2.453931 : 367.6323 : 1417.172 :
 ? 25 T-C-L-C  =2841.204 : 3.284871 : 1121.051 :
 ? 38 PI-C-C-C  =20.33646 : 26032.65 : 170.4399 :
   16 T-SS-C-LCS  =478.1066 : 2.41061 : 1263.271 :
 ? 20 T-L-L-C  =5.201629E-02 : 18.33595 : 850.5664 :
 ? 30 T-LCS-C-SS  =7.800847E-02 : 820.8613 : 148.7805 :
 SAVE TO FILE  ? NETWORK3.LIB

         MENU
 1 - LOAD ANTENNA IMPEDANCE FILE
 2 - DETERMINE NETWORK CANDIDATES
 3 - OPTIMIZE SELECTED NETWORK
 4 - ADJUST COMPONENT VALUE MANUALLY
 5 - LIST NETWORK CANDIDATES
 6 - DIGITIZE IMPEDANCE PLOT FROM TABLET
 7 - EXIT
 SELECTION (1-7) ? 7
```

There are 12 network candidates, namely network numbers 17, 35, 21, 33, 36, 28, 18, 25, 38, 16, 20, and 30. Network number 17 is ranked best among these network candidates. Actually, network number 17 with the calculated component values is an acceptable network which provides a maximum VSWR of 2.8:1 over the operating band from 2 to 6 MHz. No further optimization process is required. The network number 17 is shown below:



$L_1 = 7.400042\ \mu H$

$C_1 = 591.4796\ pF$

$L_2 = 1.677851\ \mu H$

6. SUMMARY AND RECOMMENDATIONS

An interactive BASIC language computer program to aid in design of a matching newwork for a broadband antenna has been described and guidelines for the design of a broadband matching network presented. The ANTMAT program provides a computer-aided design tool for determining network topology and element values of the networks. It improves the speed and accuracy of the broadband matching network design procedure. An optimzation algorithm finds the values of the elements that minimize the input reflection coefficient. At first, the optimization algorithm with an exponential weighting function is employed for determining a list of network candidates (either a pi network or a T network) from which a network topology is selected. After a topology is specified, the optimization algorithm with other weighting functions is used for finding optimum element values. A sample problem to illustrate the use of the ANTMAT program is included.

Given a network topology, the minimization of the input reflection coefficients in the ANTMAT program has been formulated as an unconstrained optimization problem. The method of Steepest Descent is used here. We suggest that other unconstrained optimization algorithms such as NL2SOL, which is an adaptive nonlinear least-squares algorithm (Reference 8), should be investigated. Furthermore, we suggest that there may be an advantage to using a constrained optimization formulation such as the following:

Optimize

$$f(p_1, p_2, p_3) = \sum_{i=1}^{N} W_i \, |\Gamma_i|^2 \tag{6-1}$$

subject to

$$|\Gamma_i|^2 \leq 0.5 \ , \tag{6-2}$$

$$0.25 \ \mu H \leq L \leq 12 \ \mu H \ , \tag{6-3}$$

and

$$50 \ pF \leq C \leq 2500 \ pF \ , \tag{6-4}$$

where bounds in the constraints are for illustration purposes and can be specified as required. Mathematically, the constrained optimization formulation describes the problem better than does the unconstrained optimization formulation. However, solving a constrained optimization problem requires a more complex algorithm such as the Fiacco and McCromick method (Reference 9) and more computer time. An application of the Fiacco and McCromick method is given in Reference 10. A further study of this approach is recommended.

The matching network considered in this report is a lossless two-port network consisting of only inductors and capacitors. We recommend an extension of the element types to include ideal transformers. Some cases require the use of an ideal transformer to achieve the desired performance. Wideband matching transformers are commercially available for HF band at 1 kW power level (Reference 11). These wideband matching transformers are not ideal transformers and use ferrite elements. An investigation of intermodulation interferences caused by the ferrite elements of the wideband matching transformers in a cosite shipboard environment is recommended. It seems that the installation of wideband matching transformers at sho stations has a better chance of success than the shipboard application.

7.0 REFERENCES

1. W.K. Chen, *Theory and Design of Broadband Matching Networks*, Pergamon Press Ltd., Oxford, Great Britain, 1976, Chapter 4.

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APPENDIX A

PRODUCING A SMITH CHART

This appendix describes mathematically the construction of the Smith Chart (Reference 12) used in the Antenna Matching Program. The program displays and plots impedance data on the Smith Chart as shown in Figure A-1 and also creates the Smith Chart on blank 8-1/2- by 11-in. paper. Other computer programs, written in FORTRAN IV, for plotting impedance or admittance data on a Smith Chart can be found in References 13 and 14.

The Smith Chart is a chart composed of two families of mutually orthogonal circular coordinate curves representing rectangular components of impedance or admittance normalized with respect to the characteristic impedance and/or characteristic admittance of a waveguide. A conformal transformation,

$$W = f(z) = \frac{z - 1}{z + 1} \qquad \text{(A-1)}$$

can be applied to construct the Smith Chart.

Let each point on a rectangular chart be denoted by a complex number

$$W = u + jv \ ,$$

where W represents a normalized impedance. Similarly, let each point on the circular chart (the Smith Chart) be denoted by a complex number

$$z = r + jx \ .$$

The mapping of Equation (A-1) moves all points on the right-hand side of the W-plane ($u \geq 0$) inside (or on) a circle of unit radius in the Z-plane.

Now suppose we draw two intersecting curves in the W-plane and the corresponding curves in the Z-plane. The conformal transformation preserves the angles of intersection. The angle of intersection of the two curves in the W-plane is the same as the angle of intersection between the corresopnding curves in the Z-plane, unless the intersection point is a singular point of f(Z). By using Equation (A-1), straight lines parallel to the rectangular coordinate axes can be transformed into orthogonal circular coordinate curves which represent the Smith Chart.

The circles of constant VSWR can be drawn on the Smith Chart. The center of the circles is at the origin of the Z-plane. The radius of circles is the magnitude of voltage reflection coefficient. The VSWR and the voltage reflection coefficient are related by Equation 3-1 of section 3.

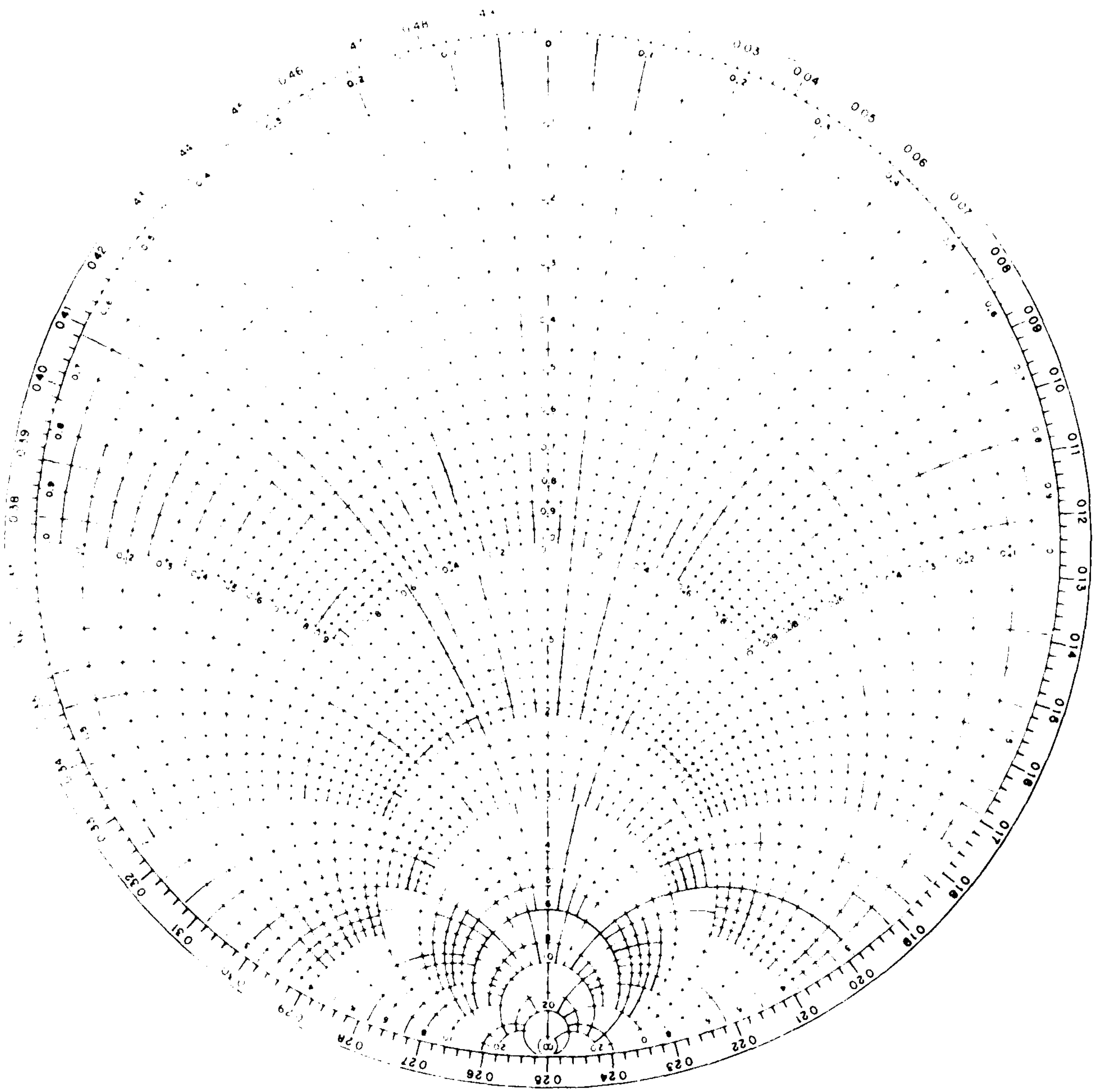

Figure A-1. Impedance diagram (Smith).

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